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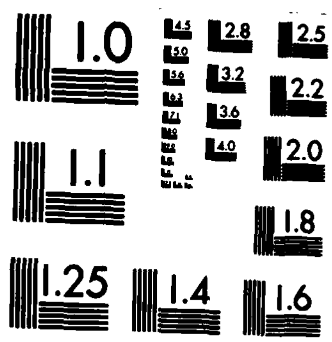
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AD-A154 470

A SURVEY OF WIND AND TURBULENCE MODELING METHODS

FINAL REPORT

CONTRACT NO. DAAH01-84-D-A005

DELIVERY ORDER 0030

Principle Investigator - George D. Edgemon

AD-A154 470

MARCH 13, 1985

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO AD-A154 470	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Survey of Wind and Turbulence Modeling Methods		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) George D. Edgemon		8. CONTRACT OR GRANT NUMBER(s) DAAH01-84-D-A005 Delivery Order 0030
9. PERFORMING ORGANIZATION NAME AND ADDRESS Control Dynamics Company Suite 1414, Executive Plaza, 555 Sparkman Dr. Huntsville, AL 35805		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Commander: US Army Missile Command ATTN: AMSMI-RDD Redstone Arsenal, AL 35898-5252		12. REPORT DATE 13 March 1985
		13. NUMBER OF PAGES 82
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release, Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Wind Modeling
Turbulence Modeling
von Karman Spectra
Coherence

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this survey was to determine the type of work being done in the field of wind and turbulence modeling as related to the problems encountered in the use of free-flight flat-fire rockets in the atmospheric boundary layer. In addition, it was desired that the modeling techniques which seemed particularly relevant be explained from an applied engineering point of view.

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The first section of this report contains a summary of surveys of the available literature relevant to modeling low level winds. The second section to this report consists of a summary of meetings and phone contacts between Control Dynamics and various authorities in the fields of atmospheric science. Section 3 consists of definitions of some commonly encountered terms used to describe the assumptions used in modeling turbulence. Sections 5 through 8 consist of discussions of specific work which appears relevant to the modeling of wind with regard to rocketry problems. These topics include the approximation of the von Karman turbulence spectra with a rational function, effects of atmospheric stability on turbulence, data available on mean winds and standard deviations, and the spatial modeling of wind and turbulence.

CONTENTS

LIST OF FIGURES

1. INTRODUCTION

This final report consists of a summation of results of a survey conducted by Control Dynamics Co. from December 1984 through February 1985. The purpose of this survey was to determine the type of work being done in the field of wind and turbulence modeling as related to the problems encountered in the use of free-flight flat-fire rockets in the atmospheric boundary layer. In addition it was desired that the modeling techniques which seemed particularly relevant, be explained from an applied engineering point of view.

The first section of this report contains a summary of surveys of the available literature relevant to modeling low level winds. The second section to this report consists of a summary of meetings and phone contacts between Control Dynamics and various authorities in the fields of atmospheric science. Section 3 consists of definitions of some commonly encountered terms used to described the assumptions used in modeling turbulence. Sections 5 through 8 consist of discussions of specific work which appears relevant to the modeling of wind with regard to rocketry problems. These topics include the approximation of the von Karman turbulence spectra with a rational function, effects of atmospheric stability on turbulence, data available on mean winds and standard deviations, and the spatial modeling of wind and turbulence.

2. SURVEY OF AVAILABLE LITERATURE

A survey of literature relevant to boundary layer wind effects on flat fire rockets was conducted through several channels. The majority of the survey consisted of literature searches through the Redstone Scientific Information Center (RSIC) of the following data bases.

1. Defense Technical Information Center (DTIC)
2. NASA Recon
3. Journals and reference material

Additional information was obtained from direct contacts with several people working in the field of wind and turbulence research.

Approximately 80-90 papers have been identified as having some degree of relevance to this task. These documents fall roughly into the following categories.

1. Handbooks
2. Terrain effects
3. Space - time relationships
4. Flat - fire trajectories
5. Wind profiles, studies, ect.
6. Modeling
7. General turbulence analysis
8. Misc.

The majority of these deal with the simulation, modeling, or representation of various types of low - level turbulence. All documents obtained by Control Dynamics have been listed in an extensive bibliography in the last part of this report. Because of the number of reports, the bibliography has been broken down into sections roughly according to topic as shown above. All references in this report will have the following form.

(category number . document number)

For example, (1.1) would refer to the document in the

Handbooks section by Cole, Grantham, Gringorten, Kantor, and Tattleman.

Copies of several of the more pertinent documents have been included as attachments to this report. A list of attachments follows the Appendix.

3. MEETINGS AND PHONE CONTACTS

Several meetings and phone conversations have been held regarding the wind project. These are listed in roughly chronological order with the highlights of each contact.

MEETINGS

1. Dr. Oscar Essenwanger 12-4-84 MICOM - Research Directorate

   Discussed the availability of instrumentation capable of measuring at high frequencies (> 1 Hz.). Best data available from his office is at 1 second but is all very low speed (< 4 m/s). Next best data is at 6 second intervals. Dr. Essenwanger considers terrain to be the most important factor in low level turbulence.

2. Don Combs and Dick Dickson - 12/5/84 - MICOM

   Discussed objectives of the contract and the delivered scope of work. Basic objective was for a general study which did not focus on a particular missile system. It was desired to look at the flat fire scenario in the atmosphere below 200 meters. Material was reviewed and received from D. Dickson on some basic sources of information.

3. Dr. Warren Campbell 1-8-85 Systems Dynamics Lab (MSFC/NASA)

   A meeting was held with Dr. Campbell to discuss several issues with which he is knowledgeable. These include the Space Shuttle Turbulence Tapes (SSTT), rational approximation of the von Karman turbulence spectra, and the inclusion of cross correlation factors into turbulence models. The SSTT are available for use. Several points regarding their applicability were discussed as follows:

   1. The SSTT are generated over a frequency range based on the size of the vehicle in question (Space Shuttle), thus to be applied to short tactical rockets the tapes would need to be regenerated. If it was desired to use the tapes with larger strategic missiles, the present tapes would seem applicable.

   2. SSTT data exists im six separate altitude bands and was generated with differing sample rates in

various bands. If the tapes were to be used for simulation of lofted missile trajectories which pass through more than one band, the variations in sample rate would have to be allowed for.

3. Use of the tapes in simulation work requires the use of a computer with sufficient storage capability to store the entire turbulence time series needed for a simulation run in a file. The simulation would then read data from mass storage as it ran.

4. The SSTT time series have been analyzed statistically and have been shown to possess very good spectral characteristics. The tapes exhibit a -5/3 rolloff as associated with the von Karman spectra.

A paper was received from Dr. Campbell regarding a method for approximating the von Karman spectra by a rational expression. The technique used shows extremely good approximation to the theoretical von Karman spectra. Use of an approximation would allow the modeling of the more accurate von Karman spectra without the associated difficulty of simulating the irrational von Karman expressions. Dr. Campbell delivered two computer programs to Control Dynamics which use the approximate von Karman techniques to produce turbulence time series. An elaboration on this work will be presented in a following section.

A technique which is currently under study by Dr. Campbell was presented for the inclusion of cross correlation terms into the turbulence models. The technique involves the process of filtering various white noise inputs and summing the outputs through filters to produce turbulence with the desired cross correlation and spectra.

Two additional sources of information were suggested as follows:

1. Models have been developed by Paul Reeves to simulate the patchy or modulated characteristics of turbulence.

2. It was suggested that Dr. Walter Frost in Tullahoma Tenn. (UTSI - University of Tennessee Space Institute) be contacted for a knowledgeable source of information on both flight mechanics and turbulence modeling.

4. Dr. Oscar Essenwanger 2-11-85 MICOM - Research Directorate

A follow-up meeting was held with Dr. Essenwanger to clarify information received in a meeting on 12-4-84. It was also desired to obtain specific information on the following topics.

a. Mean wind profiles and availability of data for the lower atmosphere.

b. Information on relative stability of the atmosphere.

c. Availability of any turbulence or any other wind model.

d. Information on any work done on correlation and coherence of turbulence.

e. Any information relating to terrain influences on wind and/or turbulence.

f. Any information concerning the non-gaussian nature of turbulence.

Work done by Dr. Essenwanger's office has been primarily limited to climatological studies with very little work done on turbulence. Although two reports have been received concerning turbulence representation, no models are available from Dr. Essenwanger. The reports that are available do not seem to be useful in the current modeling effort.

No significant work has been performed by Dr. Essenwanger's office in the area of terrain effects, correlation, coherence, or the non-gaussian nature of turbulence.

Two areas of work from Dr. Essenwanger's office appear to have relevance to low-level wind modeling. The first area consists of description of mean winds encountered for various seasons and geographic locations. This data is available from Dr. Essenwanger in the form of numerical tables. Work has also been published compiling studies of atmospheric stability observed in Frankfurt Germany and Osan Korea. This study should provide insight into the relative occurrence of stable, unstable, and neutral conditions in the atmosphere. This information will aid understanding the area of applicability of various turbulence models.

5. Dr. Warren Campbell 2-22-85 Systems Dynamics Lab (MSFC/NASA)

   A second meeting was held with Dr. Campbell to discuss the spatial nature of turbulence. Various approaches for incorporating coherence into turbulence models were discussed. Dr. Campbell is currently working on methods to model turbulence with coherence by the use of Monte Carlo techniques using linear filters. These techniques show promise of providing turbulence simulations that approximate the von Karman spectra and include coherence.

   Also discussed were the relative merits of Taylor's hypothesis to describe the spatial characteristics of the wind. It has been shown that over uniform terrain Taylor's hypothesis is valid.

6. Dr. Walter Frost 2-25-85 UTSI - FWG Associates

   A meeting was held with Dr. Frost in order to discuss his work in the area of turbulence and atmospheric science research. Dr. Frost has had a wide range of experience in the field of atmospheric science and aerodynamic research. This work includes several programs in which experimental data was taken either with tower arrays on the ground or using instrumented aircraft. Dr. Frost also has developed extensive simulation capabilities. The following list contains a brief summary of projects and capabilities available from Dr. Frost.

   1. Linear filter turbulence simulations.
   2. Non-gaussian turbulence simulation.
   3. Inter-level coherence modeling.
   4. Diffusion models (particle tracking).
   5. Models based on Kaimal spectra.
   6. Test data taken at MSFC tower array to test the validity of Taylor's hypothesis.
   7. Work simulating wind shear and microbursts.
   8. Data was collected at the MSFC tower array.

9. Work has been performed with the NASA gust gradient program using an instrumented B-57 aircraft.

10. Studies of complex terrain using water tunnel simulation and video taping facilities.

11. LIDAR turbulence measurements in conjunction with the B-57 aircraft program.

12. Turbulence probability distribution studies to determine non-gaussian nature of atmosphere.

13. Flight simulator modeling of turbulence and mean wind. Turbulence and mean wind models for various types of simulation.

Dr. Frost has accumulated experience in simulating various aspects of turbulence such as occurrence of various spectra, coherence, terrain effects, ect. Use of Dr. Frost in a consulting role for future work in the area of developing more accurate simulation capabilities was discussed.

7. Dr. Walter Frost 2-27-85 UTSI - FWG Associates

A follow-up meeting was held with Dr. Frost at his facility in Tullahoma Tennessee to discuss further his capabilities with regard to tactical and other missile systems. The simulation and modeling capabilities that have been developed primarily for aircraft systems lend themselves very well to the simulation of wind effects on missiles. The capability to provide various complex computer models for turbulence and other wind effects is augmented by water tunnel simulation and video tape techniques. The ability to simulate in the water tunnel real terrain models along with missile firings and record the flow patterns on video tape provides insight into flow problems over complex terrains. This is an area which is very difficult to address with numerical modeling techniques. Dr. Frost's water tunnel work has been used in areas such as the following:

1. Prediction of the dispersion of the Space Shuttle exhaust plume and ground cloud at Vandenburg Air Force Base. The water tunnel tape clearly shows how the cloud will dispurse over the mountainous areas around the base for varying wind speeds and atmospheric stabilities.

2. Simulation of the conditions surrounding the crash of the Texasgulf jet star aircraft in a wind shear related accident. The water tunnel correctly predicted the complex wind flows and turbulence in effect at the time of the crash and was instrumental evidence in the ensuing law suits.

3. Simulation of the exhaust plume released by a missile between launch and impact to determine whether an obscurity of the target is likely to occur and to what extent.

The combination of the numerical modeling techniques with water tunnel simulation of the terrains of interest would seem to extend the insight into effects of wind on missile performance over that which is gained by numerical models alone.

PHONE CONTACTS

1. Dr. Jim Halleck DOT-Trans. Systems Center 617/494-2199 Dr. Halleck suggested the following two sources of information on low level wind and turbulence.

   1. Lo-Cat data generated by the Air Force during low-level wind studies.

   2. Boeing document produced for the FAA.

      Barr,N.,Gangaas,D. and D.Schaeffer,1974, Wind Models for Flight Simulator Certification of Landing and Approach Guidance and Control Systems. FAA-RD-74-206.

2. Dr. Al Bedard NOAA-Boulder 303/497-3000 Dr. Bedard is involved with the study of low-level organized wave activity. This activity can produce large amplitude wavetrains which cause lift forces on vehicles flying through the wavetrains. A study is currently concluding at the Boulder tower in which data (taken at 10 Hz.) was collected to study wave activity. Preliminary information has been received from Dr. Bedard with additional information to be available in approximately the March 1985 time frame.

3. Dr. Walter Frost UTSI 615/455-0631 Dr. Frost is the Director of Atmospheric Sciences at the University of Tennessee Space Institute in Tullahoma Tennessee. Dr. Frost's primary work has been in the area of wind and

turbulence simulation for use in flight simulators and to study the effects of wind and turbulence on airfoils. Work has also been done in the area of terrain effects and terrain generated turbulence modeling. Much of the terrain effects work is performed by using a water tunnel to study flow patterns around specific terrain models. Dr. Frost has also been involved with the B-57 aircraft turbulence tests and with the remote sensing of turbulence using LIDAR.

4. Bill Rodgers - NWS - 772-9876 (now retired)
Suggested Kelly Hill or Mike Susko as possible contacts at Atmospheric Sciences Lab at NASA.

5. Kelly Hill - At. Sc. NASA - 453-4175
Suggested Dr. George Fichtl (453-0875) or Dr. Warren Campbell (453-1886) as contacts in the area of low - level turbulence.

6. Dr. Warren Campbell - NASA - 453-1886
Dr. Campbell is primarily concerned with the spatial modeling of turbulence in connection with space shuttle flight simulation. He suggested several sources of material and sent several reports concerning turbulence modeling and the Space Shuttle Turbulence Tapes.

7. FAA/ATL - Suggested David Redhun as a point of contact.

8. David Redhun - FAA/DCA - (202)426-8714
Mr. Redhun is concerned with hardware installations of low - level wind shear measurement equipment. He suggested three possible contacts with DOT and NOAA.

   - DOT - Transportation Systems Center
     Dr. Jim Halleck - (617)494-2199
     Dr. David Burnham - (617)494-2579

   - NOAA - Boulder Tower
     Dr. Al Bedard - (303)497-6508

9. Jim Bilbro - NASA - 453-1597
Mr. Bilbro suggested we contact William Cliff at Battelle.

10. William Cliff - Battelle - (509)375-2024
Dr. Cliff sent two documents on the simulation of turbulence (simple model) and the simulation of the hourly wind at randomly dispersed sites.

11. Orville E. Smith - NASA - 453-3101
Mr. Smith was retiring in a few days and no information was available from him because all of his references were packed away.

12. Tom Preis (505) 678-5421
Mr. Preis was unavailable for comment on repeated phone contacts.

4. TURBULENCE NOMENCLATURE

In any discussion of atmospheric turbulence there are several terms which will be encountered. These terms are discussed in order to provide insight into the information in following sections.

1. Homogeneity - A turbulent flow is homogeneous if its statistics do not vary in space. The presence of the earth's surface is evidently important in two ways in considering homogeneity. First, statistics will vary with distance from the boundary so that it is unlikely that homogeneity could prevail, even approximately, except in the horizontal. Second, if the terrain is inhomogeneous, with hills and valleys, or with cities, fields, and forests, then the flow near the boundary can hardly be expected to be horizontally homogeneous because of the effects of the boundary on the flow itself. Homogeneous flow can be valid over rough terrain as well as over smooth terrain as long as the terrain is consistently rough along the areas of interest. It is often the case over flat and homogeneous terrain or over the ocean that small-scale flows seem to be homogeneous(7.5).

   The assumption of vertical homogeneity is almost never valid near the ground. the mean wind and temperature vary rapidly with height at first, and then somewhat less rapidly at higher altitudes.

2. Stationarity - Stationarity implies that the statistical properties of variables do not change with time. For events with time scales of hours this presents a problem due to the daily changes of the atmosphere. For scenarios such as missile launches with flight times of minutes or even seconds, the assumption of stationarity would seem to be quite valid(7.5).

3. Isotropy - Isotropy implies that the statistics of the motions are invariant to changes in directions of the coordinates, and is usually considered only when homogeneity is present in all directions. If isotropy prevails, then the variance of the three velocity components must be equal, since the variance of one component changes into that of another as the coordinate system rotates by 90 degrees. But in fact, the variances of the velocity components in the boundary layer are not the same, and for this reason alone, it is clear that the small-scale motions in the lower atmosphere are not isotropic.

Even though isotropy does not apply near the ground, local isotropy does. Local isotropy implies that not all the small-scale motions, but only the fluctuations on the very smallest-scales, are isotropic. From this hypothesis certain statistical properties of the high-frequency fluctuations can be derived. Measurements of boundary-layer turbulence have shown that these predictions are indeed satisfied, provided that the size of the eddies involved is small compared to the distance to the surface(7.5).

5. SPACE SHUTTLE TURBULENCE TAPES

One area which appears promising is the use of the Space Shuttle Turbulence Tapes (SSTT) developed by NASA for studying the effect of turbulence and gusts on the space shuttle. SSTT consists of six magnetic tapes containing time series of various types of gusts and gust gradients for six altitude bands. The tapes contain gusts u1, u2, and u3 for the X, Y, and Z axes (1,2,3) and gust gradients du2/dx1(yaw), du3/dx1(pitch), and du3/dx2(roll). The tapes were produced by a non-recursive turbulence model based on von Karman spectra with finite upper limits corresponding to the dimension's of the space shuttle. These upper integration limits increase with altitude because they are based on turbulence scale lengths (which increase with altitude) and on characteristic vehicle length in each axis. The limits are calculated according to

$$Wijmax = 1.339\ Li\ /\ lj$$

Li = turbulence scale length
lj = characteristic vehicle length

In typical use the tapes are scaled in a manner considered appropriate by the user for various standard deviation, intensities, and times. The dimensional gust is obtained by scaling the dimensionless gust by the appropriate standard deviation as follows.

$$ui^* = si\ ui$$

ui = dimensionless gust
ui* = dimensional gust
si = standard deviation

The dimensional gust gradient is obtained by scaling the dimensionless gust gradient by the appropriate standard deviation and turbulence scale length as follows.

$$\frac{dui^*}{dxj^*} = \frac{si\ dui}{Li\ dxj}$$

si = standard deviation
Li = turbulence scale

The dimensional time step is obtained by scaling the dimensionless time step by the turbulence scale length and the vehicle velocity as follows.

$$ti^* = 1.339\ Li\ Ti\ /\ V$$

Li = turbulence scale
Ti = dimensionless time step
V = vehicle velocity

Spectral analysis of each tape reveals that the simulated turbulence possesses the appropriate von Karman spectral characteristics. Both the simulated gusts and gust gradients are normally distributed with near zero means. The standard deviation of each series is constant with the theoretical energy content.(6.28&29)

The tapes containing the turbulence data as generated for the space shuttle are currently available from NASA. The source code that would be needed to regenerate the data is not currently available. New source code could easily be written by Control Dynamics using its FFT (Fast Fourier Transform) subprogram.

6. VON KARMAN APPROXIMATION

Experimental data has shown that the velocity spectra of atmospheric turbulence most closely corresponds to the von Karman spectra which is of the following form.

$$\Phi_1 = \frac{\sigma_1^2 2L_1}{\pi} \frac{1}{[1+(2\pi a L_1 f/V)^2)]^{5/6}} \qquad \text{Longitudinal}$$

$$\Phi_2 = \frac{\sigma_2^2 L_2}{\pi} \frac{1+(8/3)(2\pi a L_2 f/V)^2}{[1+(2\pi a L_2 f/V)^2)]^{11/6}} \qquad \text{Lateral}$$

Figure 1. Expressions for longitudinal and lateral von Karman spectra.

It can be seen that these spectra are irrational in form and produce a -5/3 rolloff at high frequencies.

Attempts to model these forms have resulted in two basic simulation methods.

1. Construction of a turbulence time series from the von Karman spectra requires the use of FFT (Fast Fourier Transform) techniques to generate the turbulence and storage on a mass storage device until it is needed in a flight simulation.

2. The von Karman spectra is typically approximated to the closest integer power (2) as in the Dryden spectra, so that a set of difference equations can be solved in real time during simulation to generate turbulence as needed. This method is much more efficient but provides turbulence that is less accurate.

The approximation method used by Dr. Campbell provides a higher order linear relation which closely approaches the -5/3 rolloff of the von Karman spectra as follows.

$$(1+S)^{-5/6} \approx \frac{\frac{91}{12}S^2 + 52S + 60}{\frac{935}{216}S^3 + \frac{561}{12}S^2 + 102S + 60} \qquad \text{Longitudinal}$$

The above approximation was obtained by truncating at the proper point the continued fraction expansion of the binomial function below.

$$(1+S)^V = 1 + VS + \frac{(1-V)S}{2} + \frac{(1+V)S}{3} + \frac{(2-V)S}{2}$$

$$+ \ldots + \frac{(N-V)S}{2} + \frac{(N+V)S}{2N+1}$$

For a detailed explanation of this procedure see "Monte Carlo Turbulence Simulation Using Rational Approximations to von Karman Spectra" by Dr. C.W.Campbell(6.6).

The filter function used in the transverse case is derived in much the same manner and has the following form.

$$H(s) = \frac{\left[\frac{91}{12}S^2 + 52S + 60\right]\left(1 + (8/3)^{1/2} S\right)}{\left[\frac{935}{216}S^3 + \frac{561}{12}S^2 + 102S + 60\right]\left(1 + S\right)}$$

The spectra of these approximations can be determined and compared to the irrational von Karman in order to check the validity of the approximation. Assume that a stationary random signal with a power spectral density function $\phi_x(w)$ is applied as an input to a system with a response function $H(w)$. The output from the system will be stationary random signal with a power spectral density function $\phi_y(w)$ given by

$$\phi_y(w) = |H(w)|^2 \phi_x(w)$$

By multiplying the filter functions by their complex conjugates the resulting spectra are obtained.

$$\Phi_1(w) = \frac{57.507w^4 + 1794w^2 + 3600}{18.738w^6 + 1302.507w^4 + 4794w^2 + 3600} \quad \text{Long.}$$

$$\Phi_2(w) = \frac{153.363w^6 + 4841w^4 + 11394.12w^2 + 3600}{18.74w^8 + 1321.187w^6 + 6096.447w^4 + 8394w^2 + 3600} \quad \text{Trans.}$$

where $w = 2\pi faL/V$
$a = 1.339$
L = Turbulence scale length
V = Aircraft airspeed

The following plots show the approximate spectra above plotted versus the theoretical von Karman spectra.

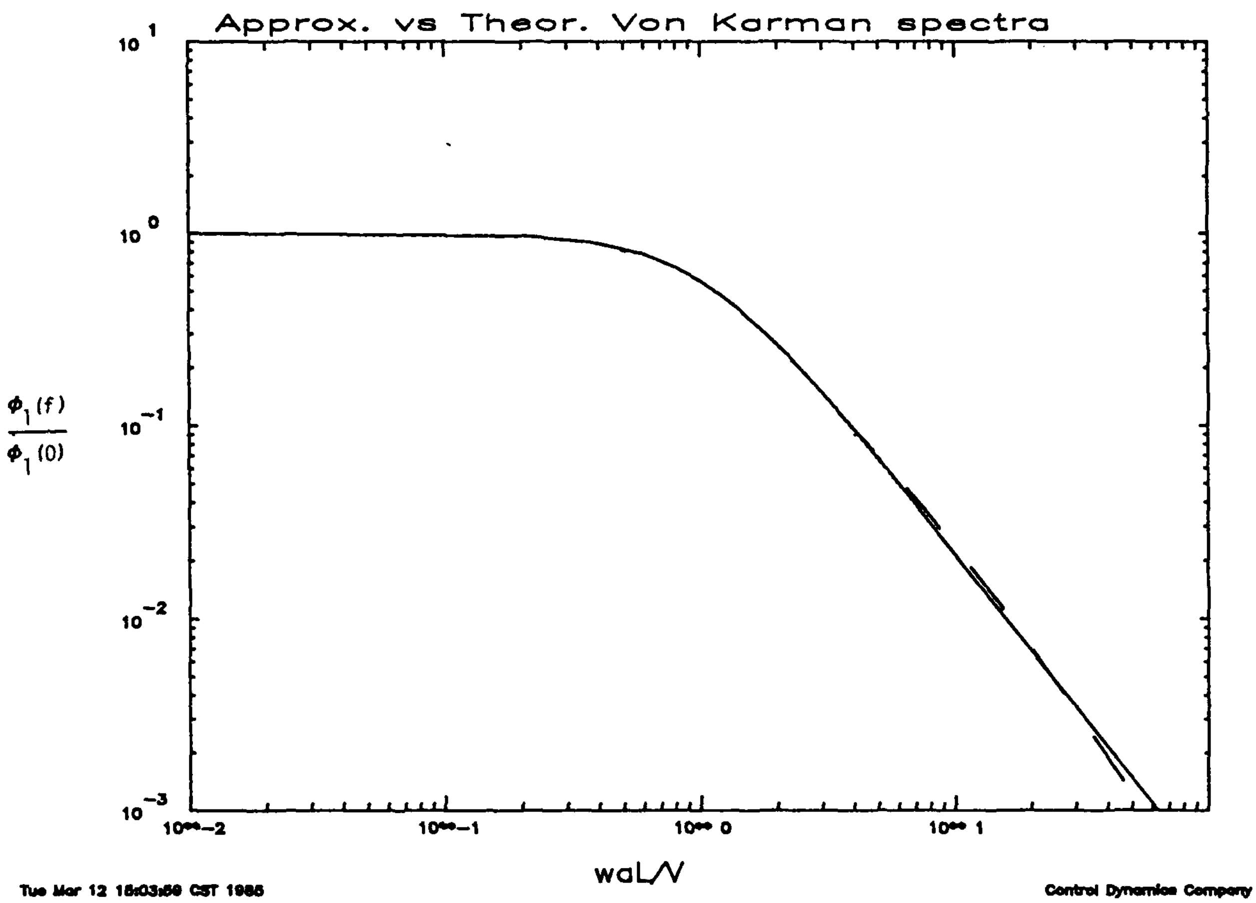


Figure 2. Approximate versus theoretical von Karman spectra - longitudinal

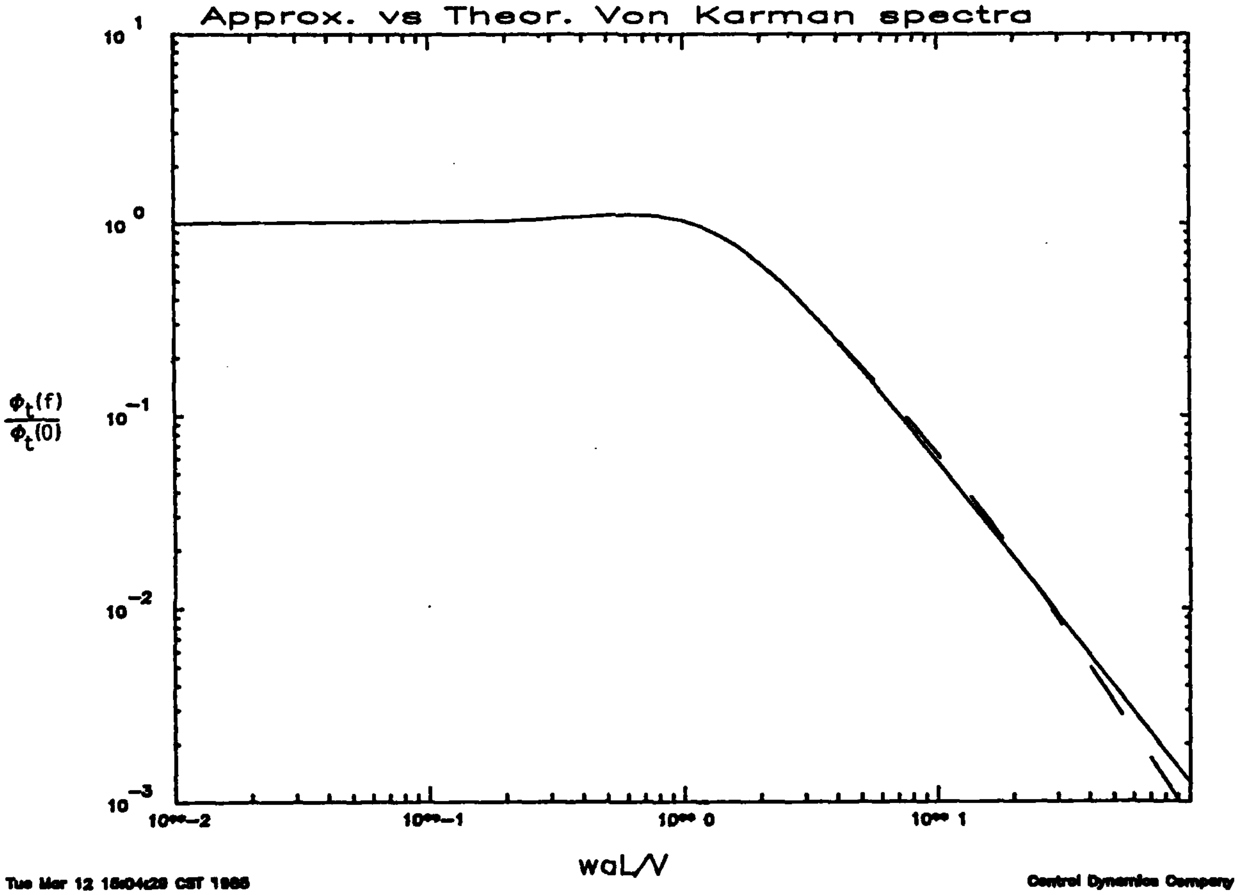


Figure 3. Approximate versus theoretical von Karman spectra - transverse

Two computer programs using this technique have been obtained by Control Dynamics Co. and modified to run on a HP9000 computer. The programs use gaussian white noise to drive a linear filter implemented as a set of difference equations corresponding to the von Karman approximation.

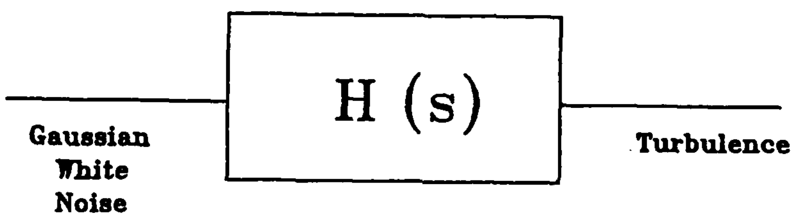


Figure 4. Turbulence generation scheme using linear filter to produce turbulence having approximate von Karman spectra

The following plots show turbulence time series and their calculated PSD's for both longitudinal and transverse cases. The turbulence was generated with gaussian white noise having standard deviation of 1.0 and mean of 0.0. The turbulence scale length was 500 meters and vehicle velocity was 100 meters/second. A 5.0 Hz. sampling frequency was used to generate 1024 points of data.

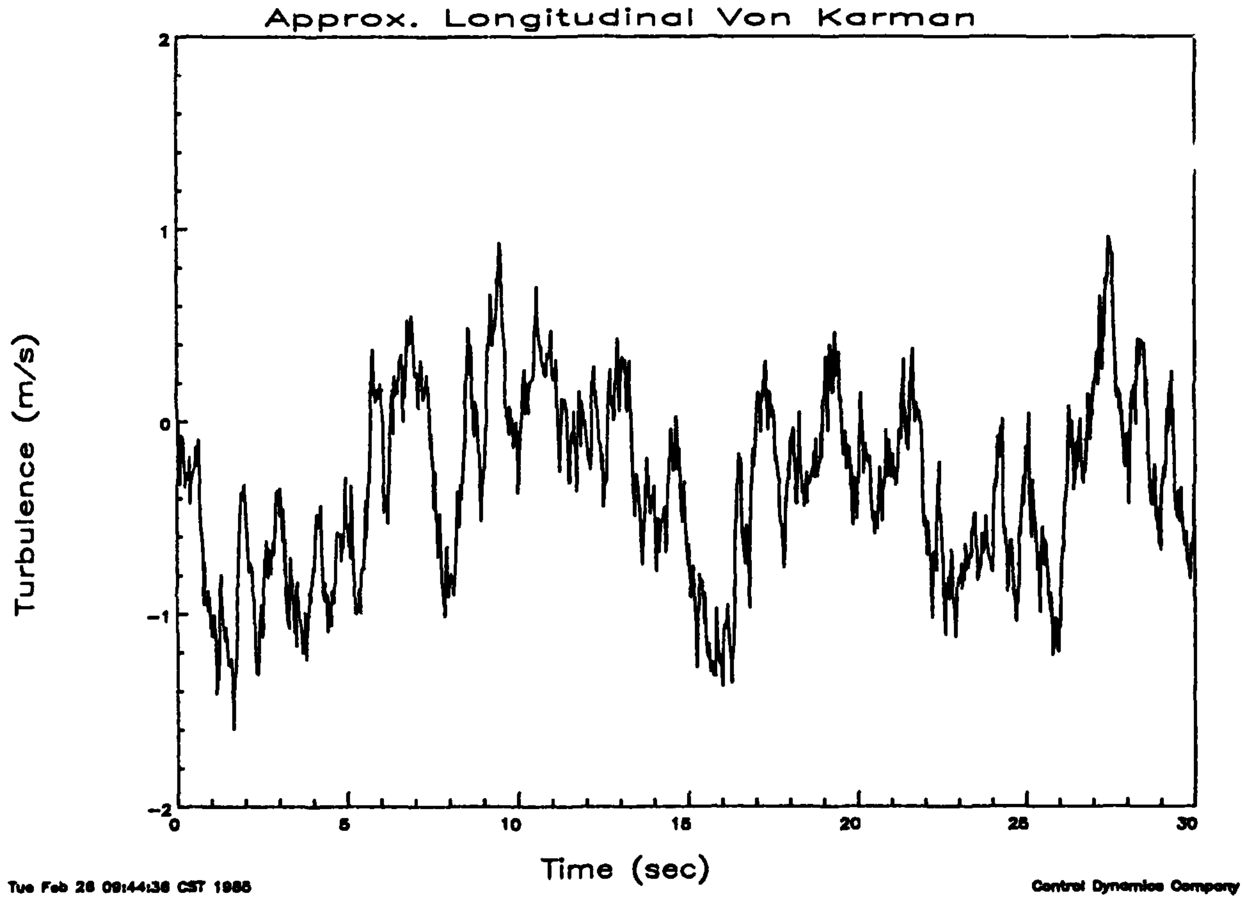


Figure 5. Longitudinal turbulence time series

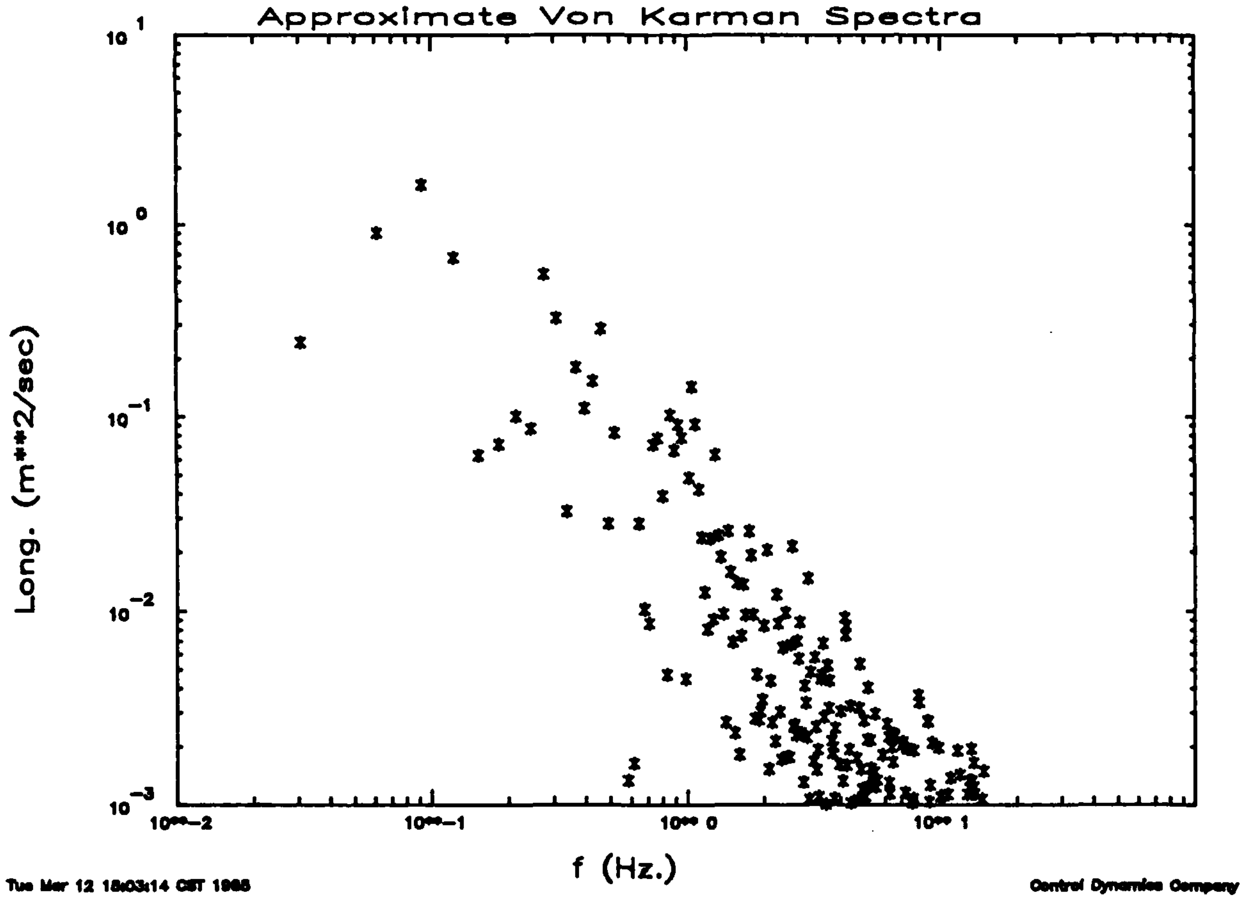


Figure 6. Velocity spectra for longitudinal turbulence

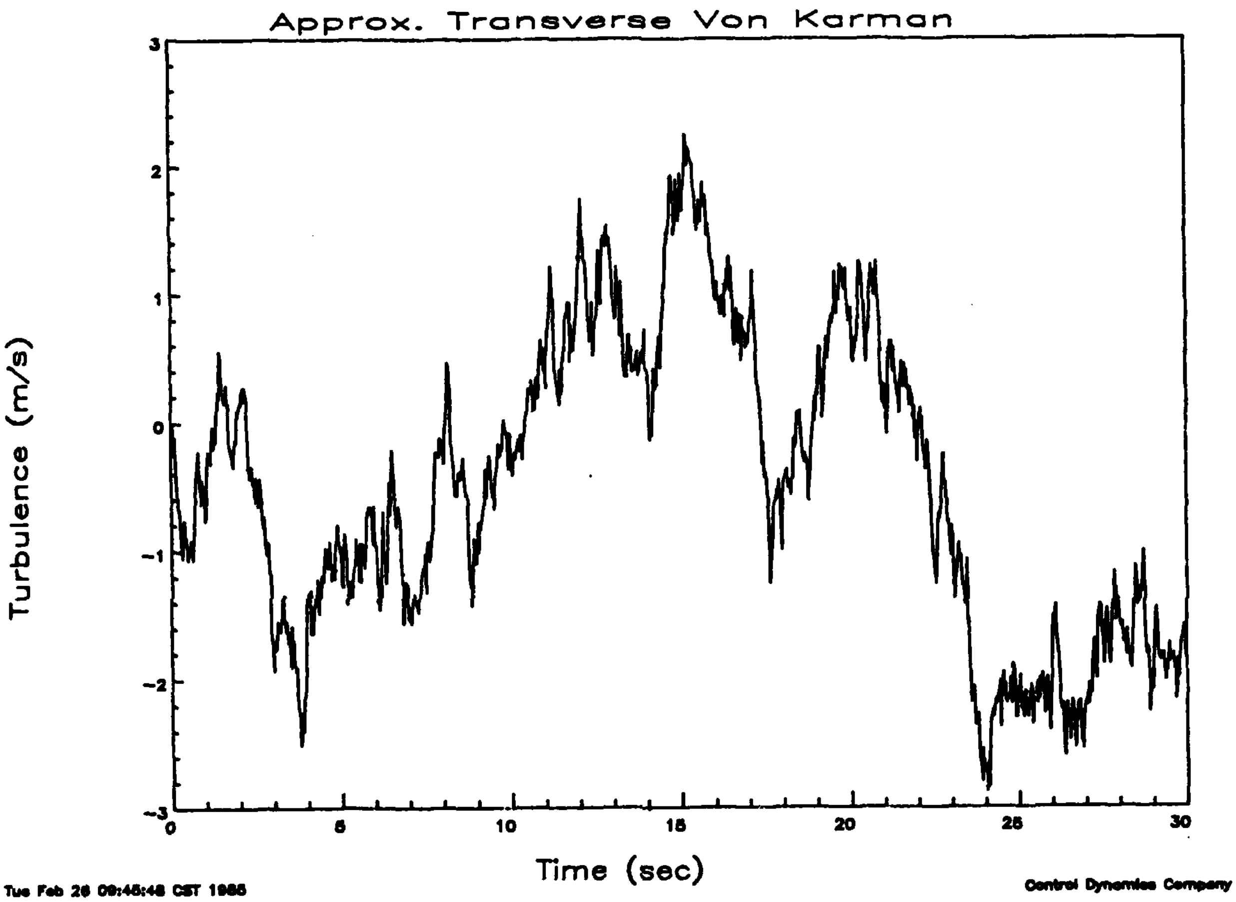


Figure 7. Transverse turbulence time series

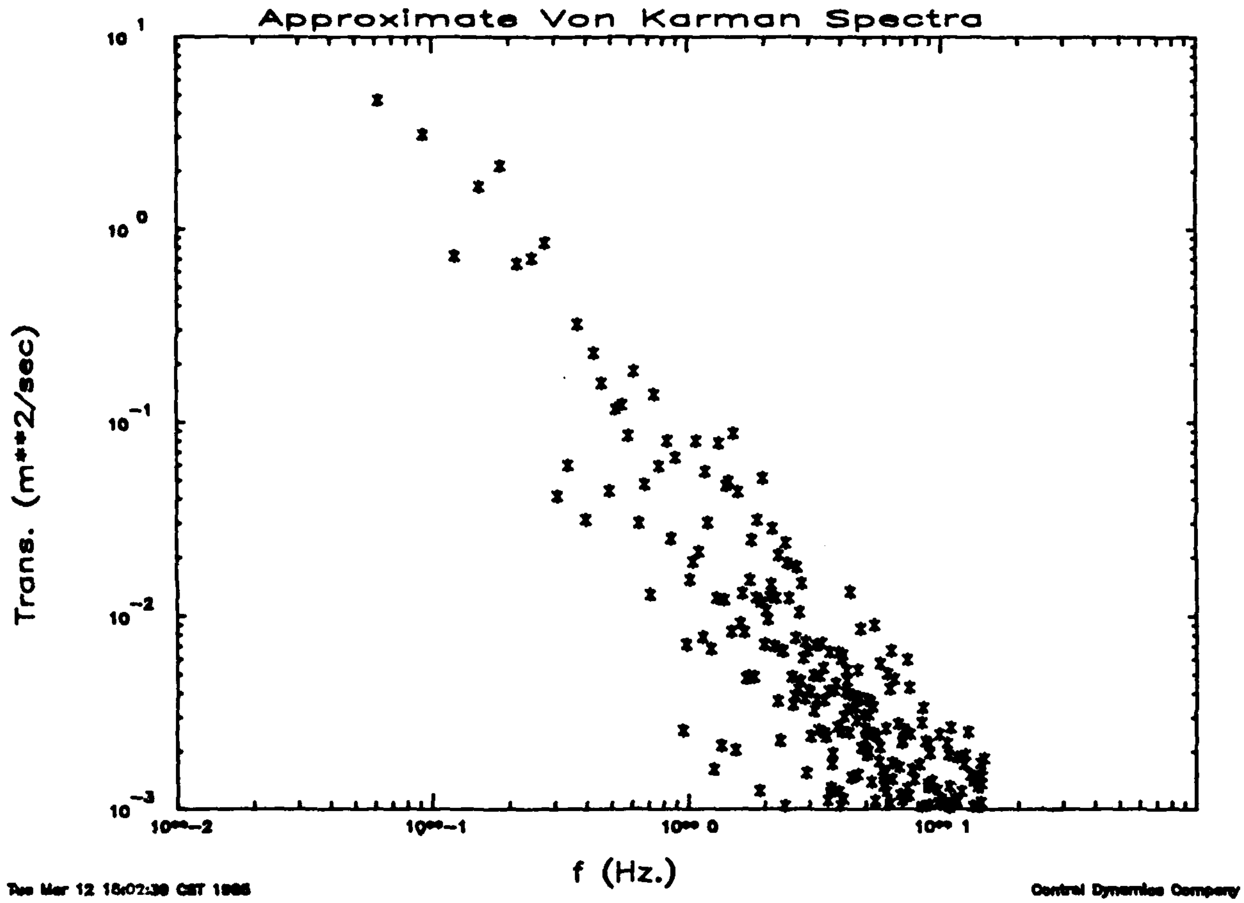


Figure 8. Velocity spectra for transverse turbulence

7. ATMOSPHERIC STABILITY

The consideration of atmospheric stability is important due to its effect on turbulence intensity. The intensity of turbulence has been shown by Frost(6.31) and others to increase with respect to the neutral case for an unstable atmosphere and to decrease for a stable atmosphere. The most commonly used turbulence spectra (such as the Dryden and von Karman) are valid for neutral conditions.

Atmospheric stability is measured by the temperature profile with altitude. A decrease in temperature with altitude is referred to as a lapse rate. An increase in temperature with altitude is referred to as an inversion.

During the daytime hours, solar radiation heats the earth more than it does the atmosphere. Conduction from the earth causes the air near the surface to be warmer than that above, and a lapse rate results. At night, with clear skies, the earth cools by radiating heat and the air next to the it cools by conduction, thus leading to inversions(6.3).

Atmospheric stability is measured by the tendency of air displaced vertically from its equilibrium condition to return to its original position. If the temperature of a parcel of displaced air decreases at the adiabatic lapse rate there exists no restoring force on the parcel and the atmosphere is said to be neutral. When a parcel of displaced air cools more quickly than the adiabatic lapse rate there is a positive restoring force tending to move the parcel, which is now cooler than the surrounding air, back toward its original position. This represents a stable atmosphere. If a parcel of displaced air cools more slowly than the adiabatic lapse rate there is a negative restoring force tending to move the parcel, which is now warmer than the surrounding air, away from its original position. This represents an unstable atmosphere.

The relative occurrences of each stability category has not been widely studied, although some data is available. Essenwanger(5.2) compiled a set of data taken in three locations in which the observed atmospheric stability was recorded for a one year period. Numerical tables were presented for data concerning the number of occurrences of each of six stability categories. The observations were grouped by time of day (0000,0600,1200,1800 GMT or local), city (Frankfurt, Hahn, Osan), and by month.

Although this data is sufficient to show general trends involved with the variation of observed atmospheric stability, the format of the data made interpretation of the

data difficult. Control Dynamics has reduced the data to bar chart form to allow easier interpretation of trends. The charts use the following conventions.

1. Each chart represents the occurrences for one year at one time of day for one city.

2. Six different criterion are established according to the Pasquil (5.2) stability criterion, very unstable, moderately unstable, slightly unstable, neutral, moderately stable, and very stable. These categories are distinguished by texture as shown on the charts legend.

3. The number of occurrences in each observed stability category is represented by the appropriately shaded region of each months bar chart. The total height of the bar indicates total observations for the month, with each textured region indicating the relative occurrences of each stability category.

By studying the charts, it becomes apparent that there exists a pronounced diurnal variation (daily) in atmospheric stability, in addition to seasonal, and geographic variations. The general patterns are as follows.

1. In each city the atmosphere is neutral to stable at midnight for all seasons.

2. In each city the atmosphere is neutral to unstable at noon for all seasons.

3. Each city shows some seasonal variation for all times, however this effect is more pronounced at 0600 and 1800 when the effect of the diurnal variation is not as strong.

4. Each city shows varying amounts of differences based on geographic location.

In summary the diurnal variation shows the most pronounced effect on stability, with the seasonal and geographic effects of lesser importance respectively.

The following figure obtained from Frost(6.31) shows measured data for stable, unstable, and neutral atmosphere's. This plot indicates the changes in the shape of the observed spectrum.

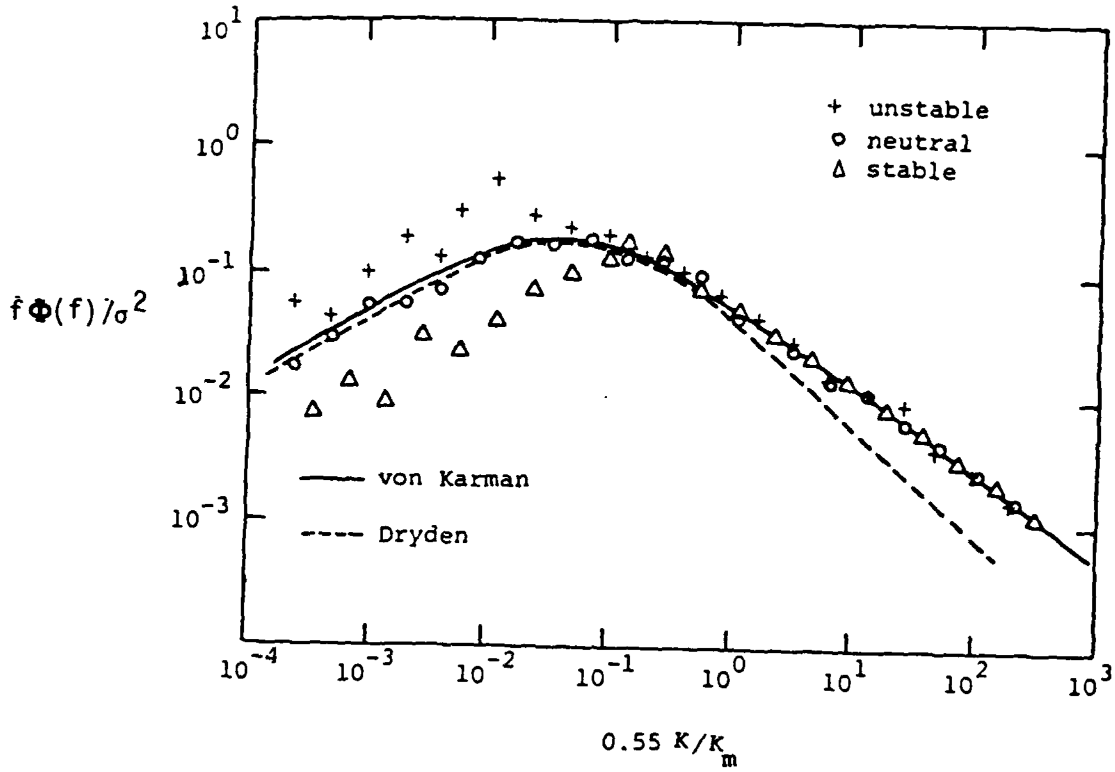


Figure 9. Measured data for stable, neutral, and unstable atmospheres vs the theoretical von Karman and Dryden spectra (Wave number K = w/v normalized by the peak scale Km of the vertical spectra.) Note: $f\phi(f)/\sigma^2$ where σ = standard deviation f = frequency.

As can be seen, the spectra of the stable, neutral, and unstable data are the same and correspond to the von Karman spectra at frequencies above the -5/3 slope break point. The value of this break point is dependent upon turbulence scale lengths and vehicle or reference velocity. At lower frequencies the data diverges somewhat from the neutral case. The figure clearly shows the effect of a stable atmosphere decreasing turbulence intensity and an unstable atmosphere increasing turbulence intensity. The neutral atmosphere corresponds to the theoretical von Karman and Dryden spectra.

In order to simulate the effects of stable and unstable atmospheres while using models with spectra corresponding to a neutral atmosphere, some modifications need to be made. One such modification that is particularly applicable to Monte Carlo simulations is the addition of a low pass filter path so that the desired lower frequencies could be scaled by a chosen gain factor as below

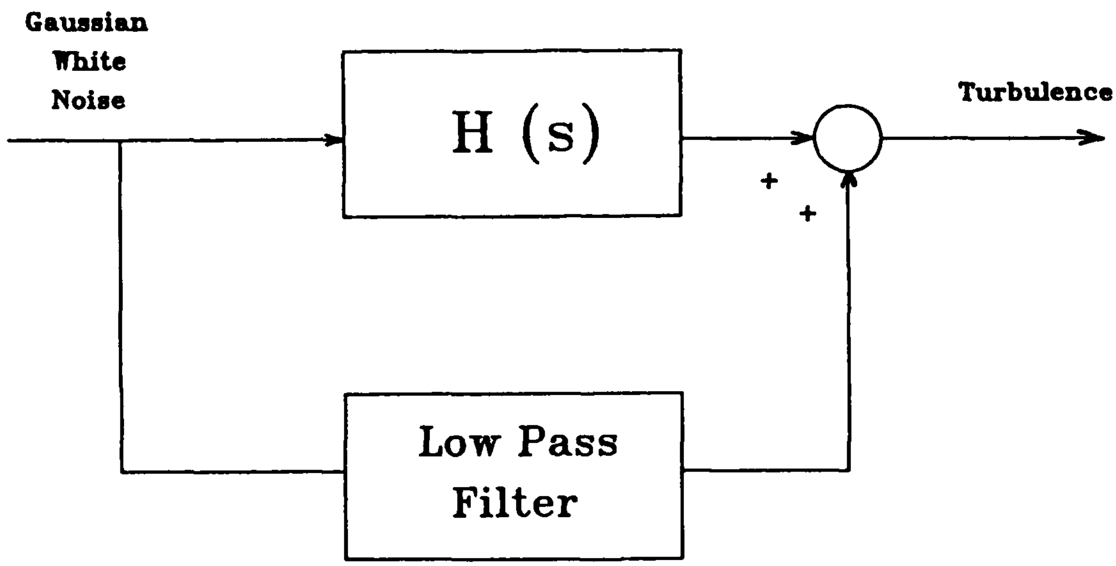


Figure 10. Method for scaling turbulence spectra for effects of atmospheric stability.

The design of this low pass filter would have to be carefully chosen so as not to overly distort the high frequency part of the turbulence spectrum.

Another method of accounting for the effects of atmospheric stability on turbulence intensity involves the use of the Kaimal turbulence spectra as presented in Frost(6.31). The Kaimal spectra consists of an empirical formula as follows.

$$\Phi(f) = \frac{\sigma^2 \quad [0.164\ (\eta/\eta o)\ ]}{f\ [1 + 0.164(\eta/\eta o)^{5/3}\ ]}$$

f = cyclic frequency
σ = standard deviation
η = the reduced frequency = fz/V
z = height
V = reference velocity

The values of "ηo" recommended by Frost for neutral conditions are

$$\eta o_1 = 0.0144$$

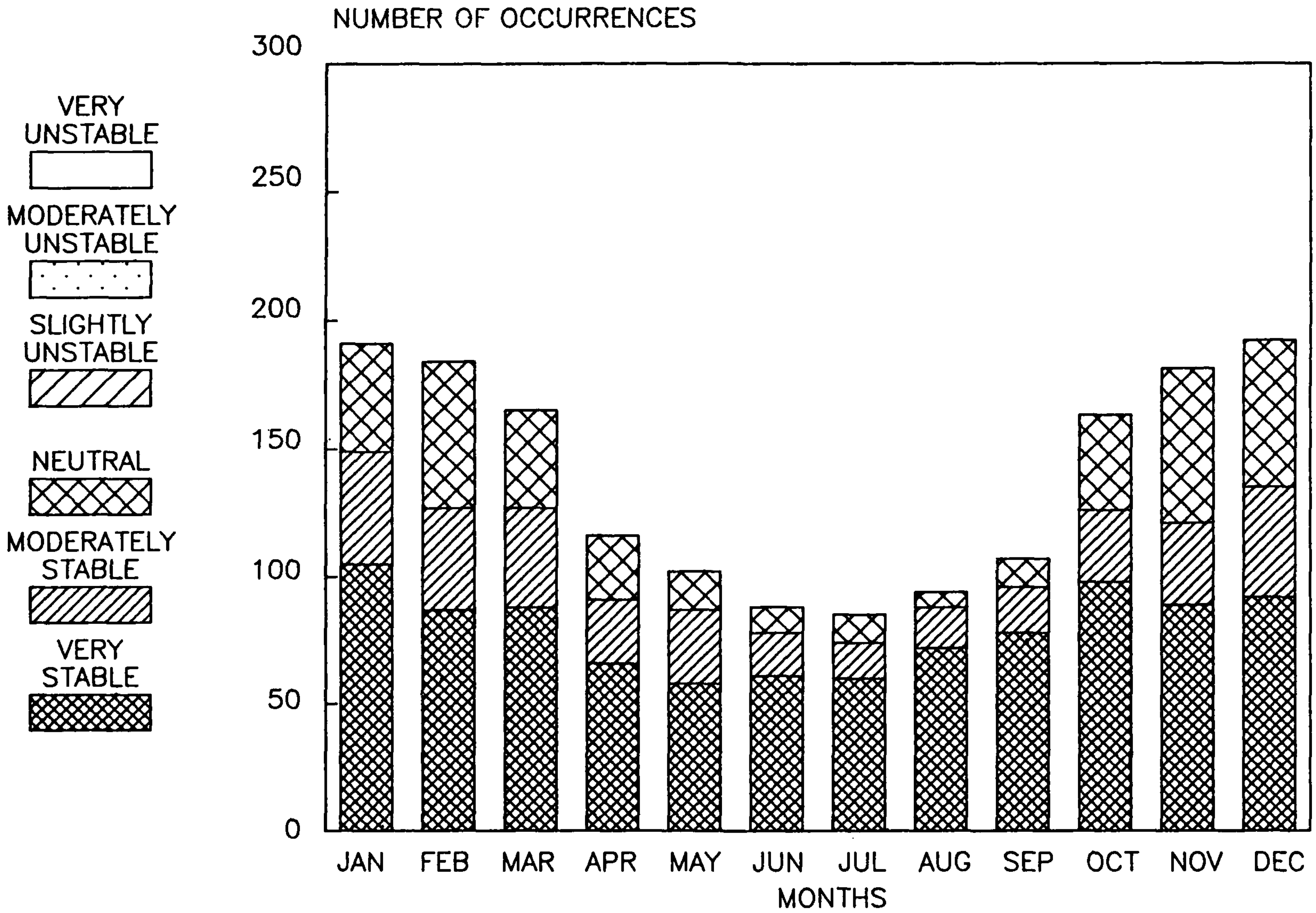
$$\eta o_2 = 0.0265$$

$$\eta o_3 = 0.0962.$$

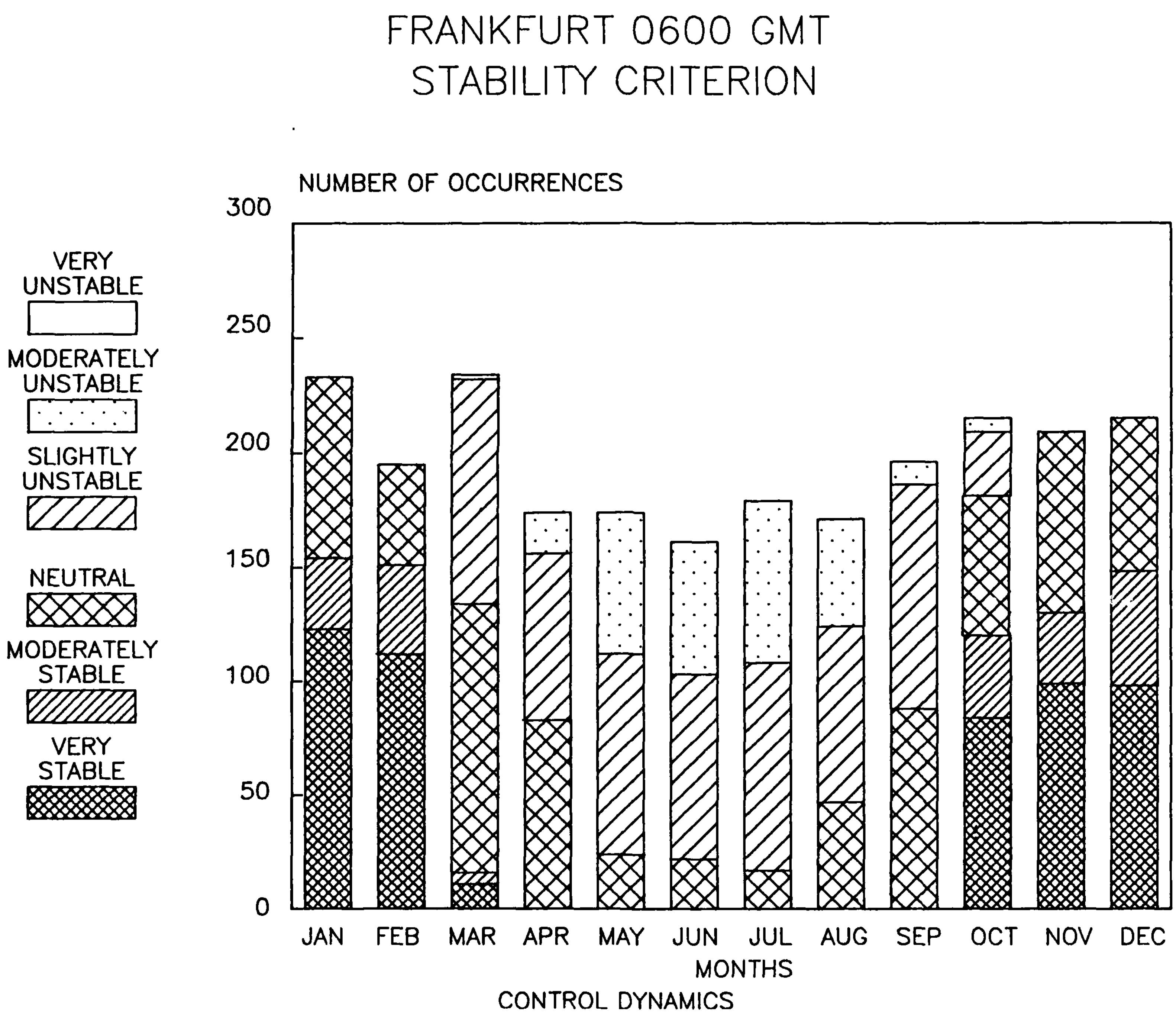
By changing these values the shape of the Kaimal spectra may be taylored to different atmospheric stabilities.

Other authors have suggested a much simpler although less accurate method of accounting for stability effects on turbulence.(5.2) The method involves the scaling of the wind's standard deviation as a function of stability. Since the turbulence spectra is directly proportional to the standard deviation, this modification causes the spectra to be shifted up or down with respect to the neutral case. This results in a spectra which becomes more accurate at low frequencies but less accurate at high frequencies. Whether this method is acceptable to a given problem can only be determined through a knowledge of the frequency ranges that are of importance to the problem being considered.

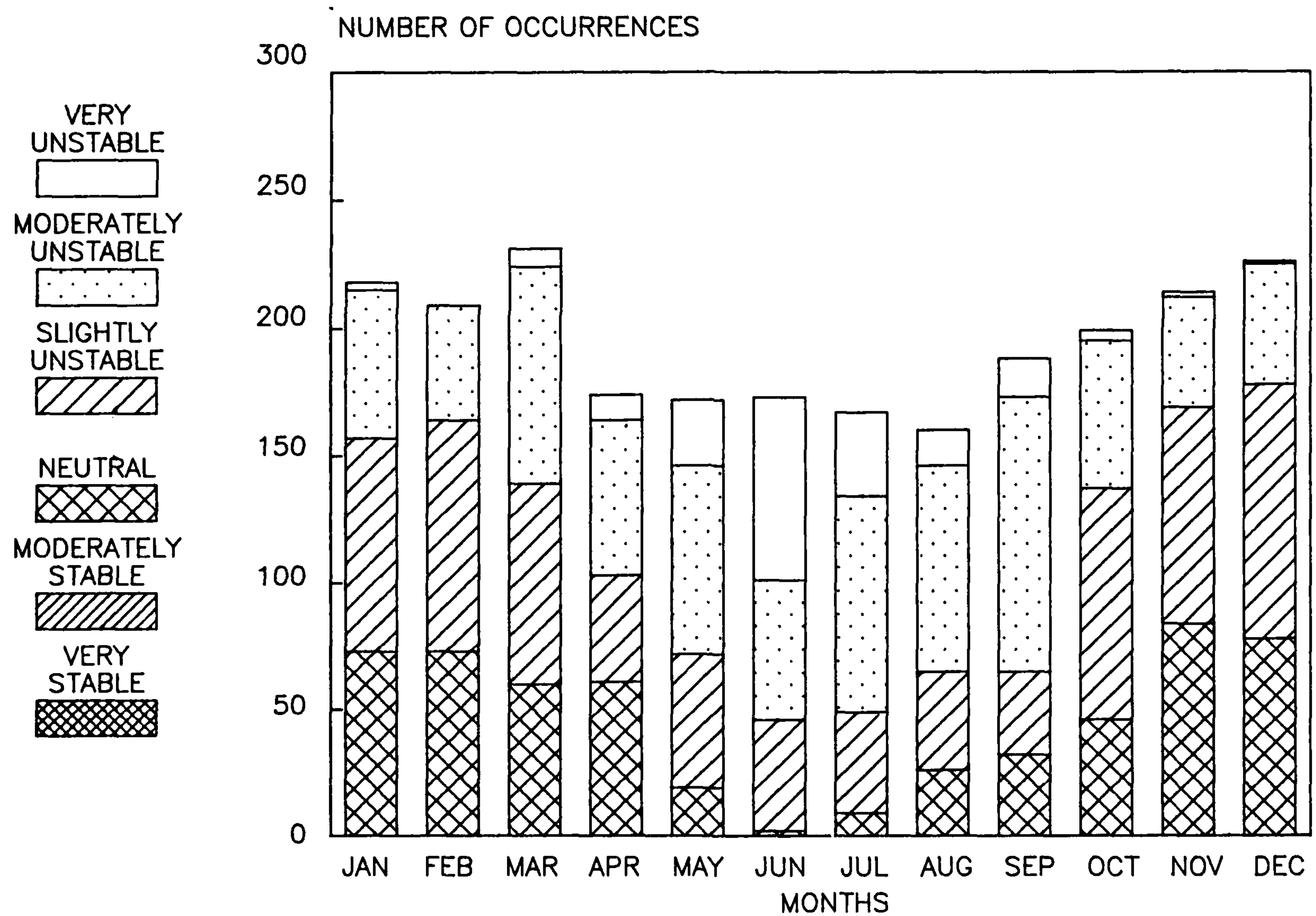
FRANKFURT 0000 GMT
STABILITY CRITERION



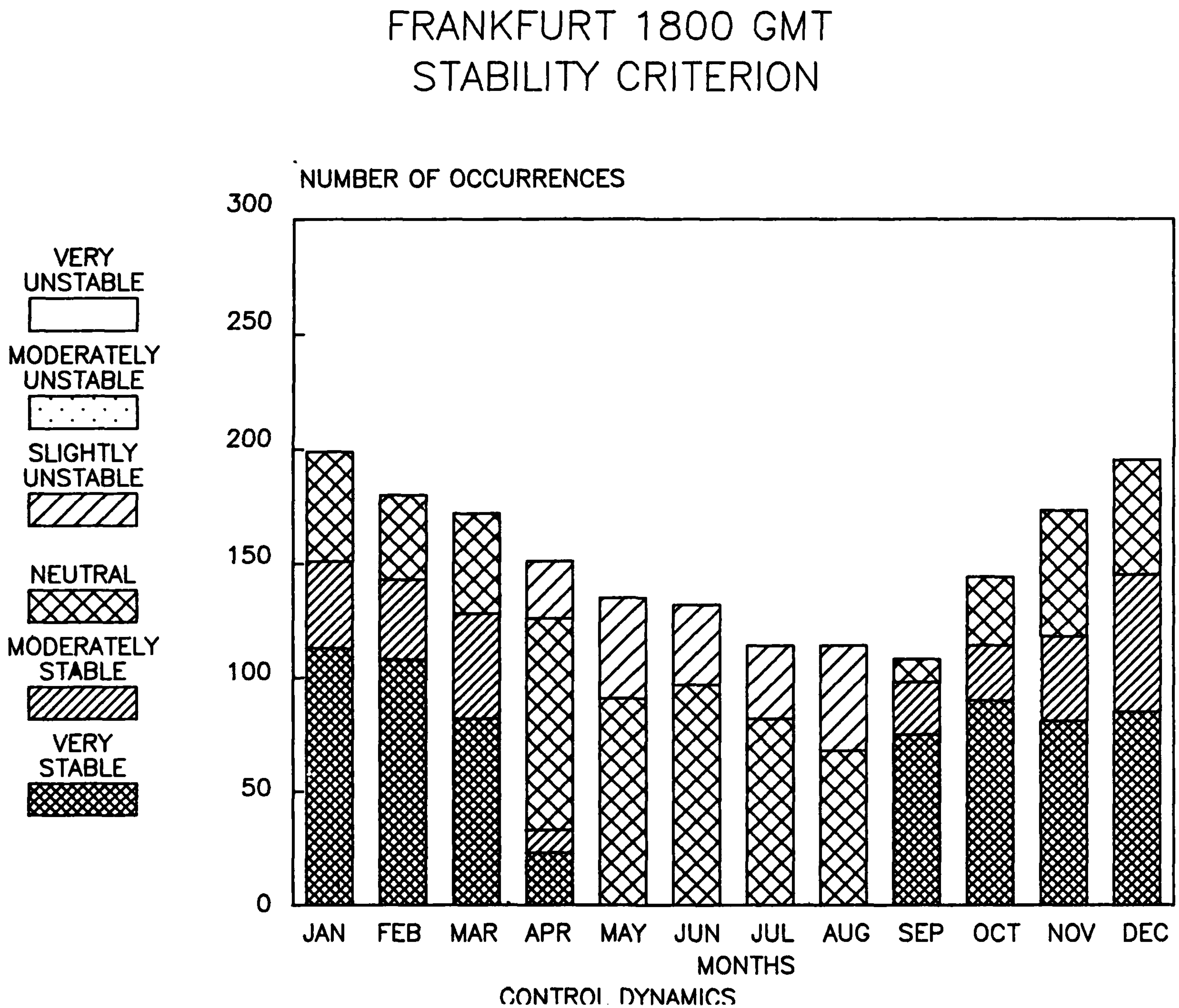
CONTROL DYNAMICS


FRANKFURT 0600 GMT
STABILITY CRITERION
NUMBER OF OCCURRENCES
300
250
200
150
100
50
0
VERY UNSTABLE
MODERATELY UNSTABLE
SLIGHTLY UNSTABLE
NEUTRAL
MODERATELY STABLE
VERY STABLE
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTHS
CONTROL DYNAMICS

FRANKFURT 1200 GMT
STABILITY CRITERION

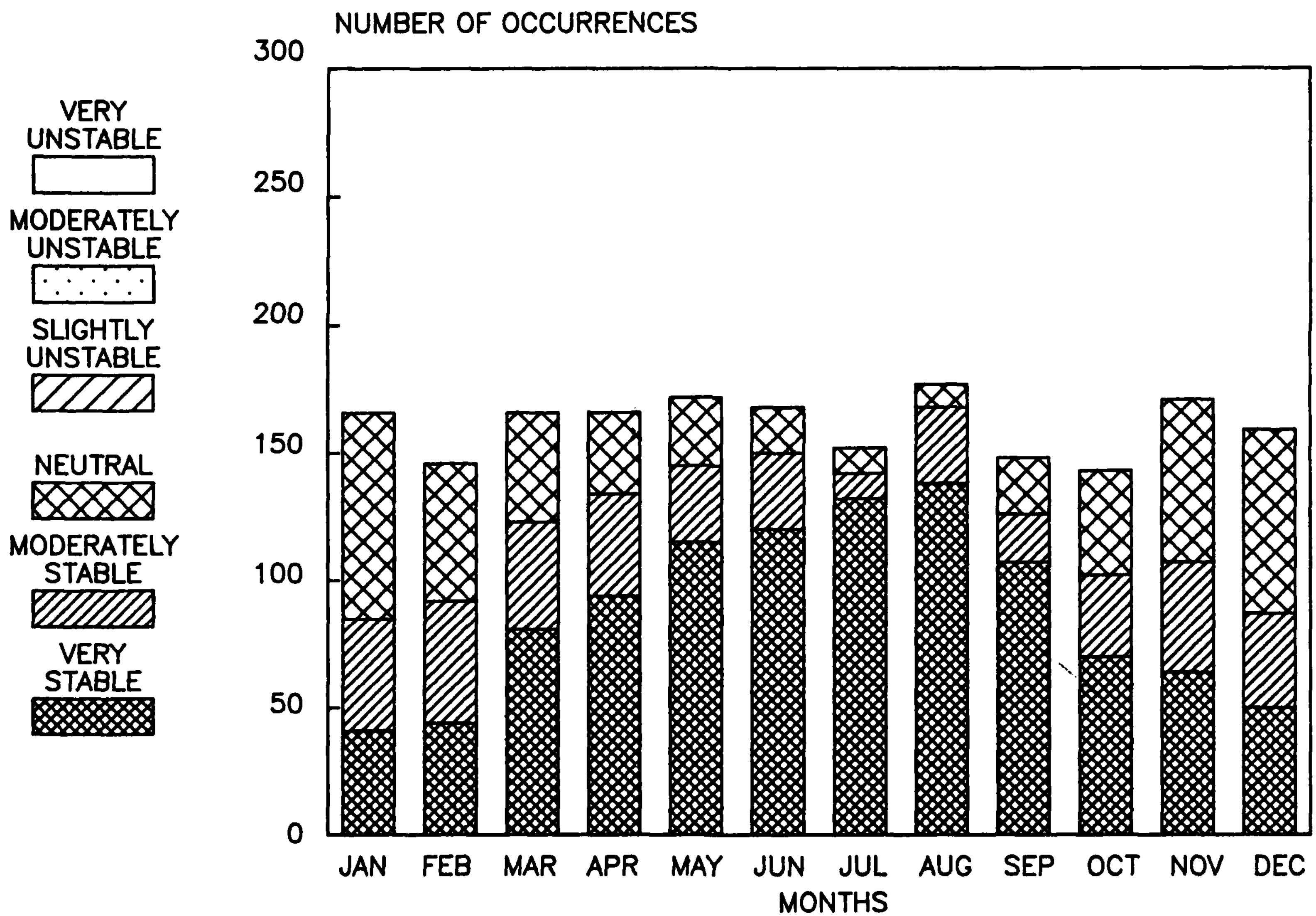


CONTROL DYNAMICS



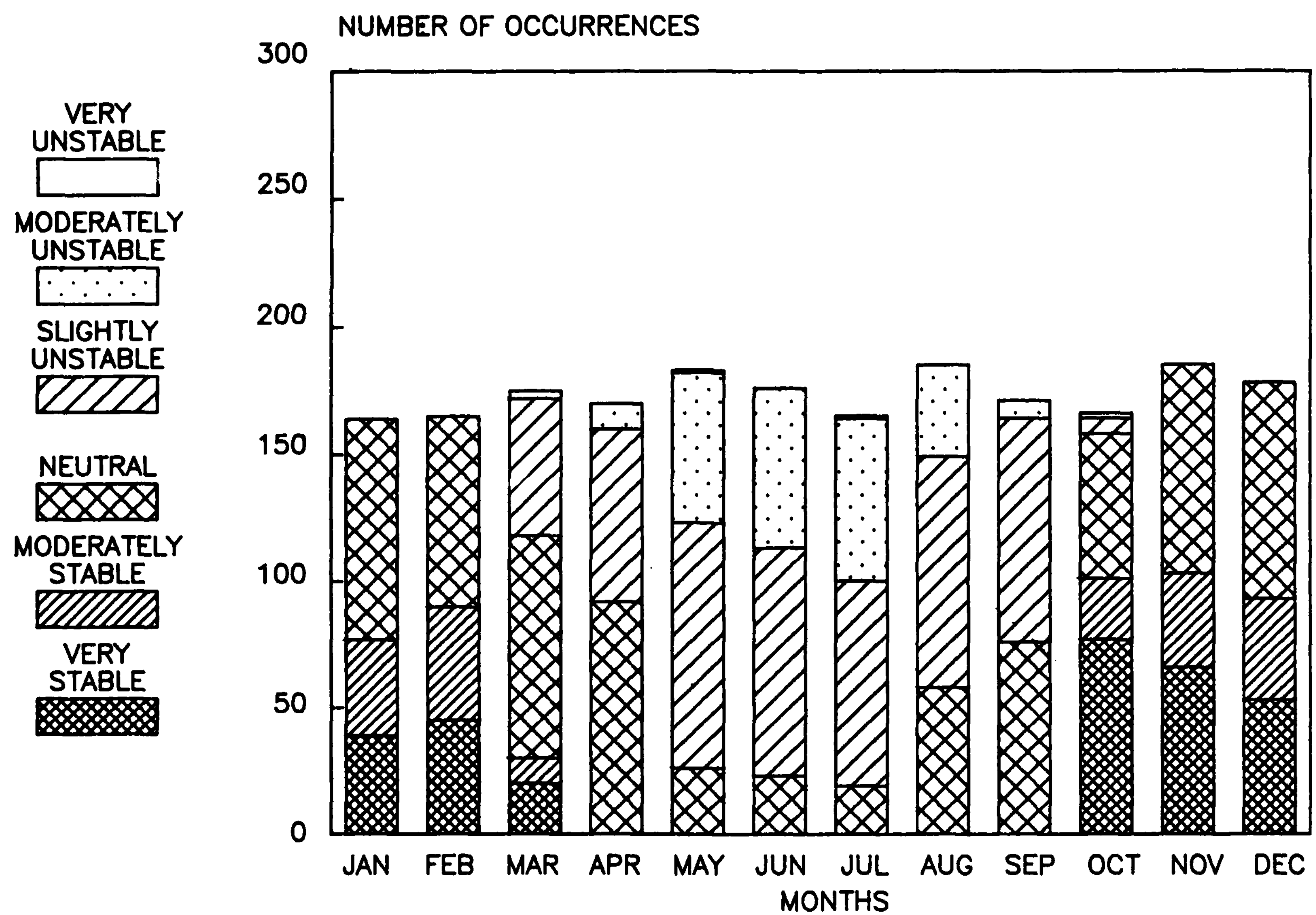
FRANKFURT 1800 GMT
STABILITY CRITERION
NUMBER OF OCCURRENCES
300
250
200
150
100
50
0
VERY UNSTABLE
MODERATELY UNSTABLE
SLIGHTLY UNSTABLE
NEUTRAL
MODERATELY STABLE
VERY STABLE
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTHS
CONTROL DYNAMICS

HAHN 0000 GMT
STABILITY CRITERION



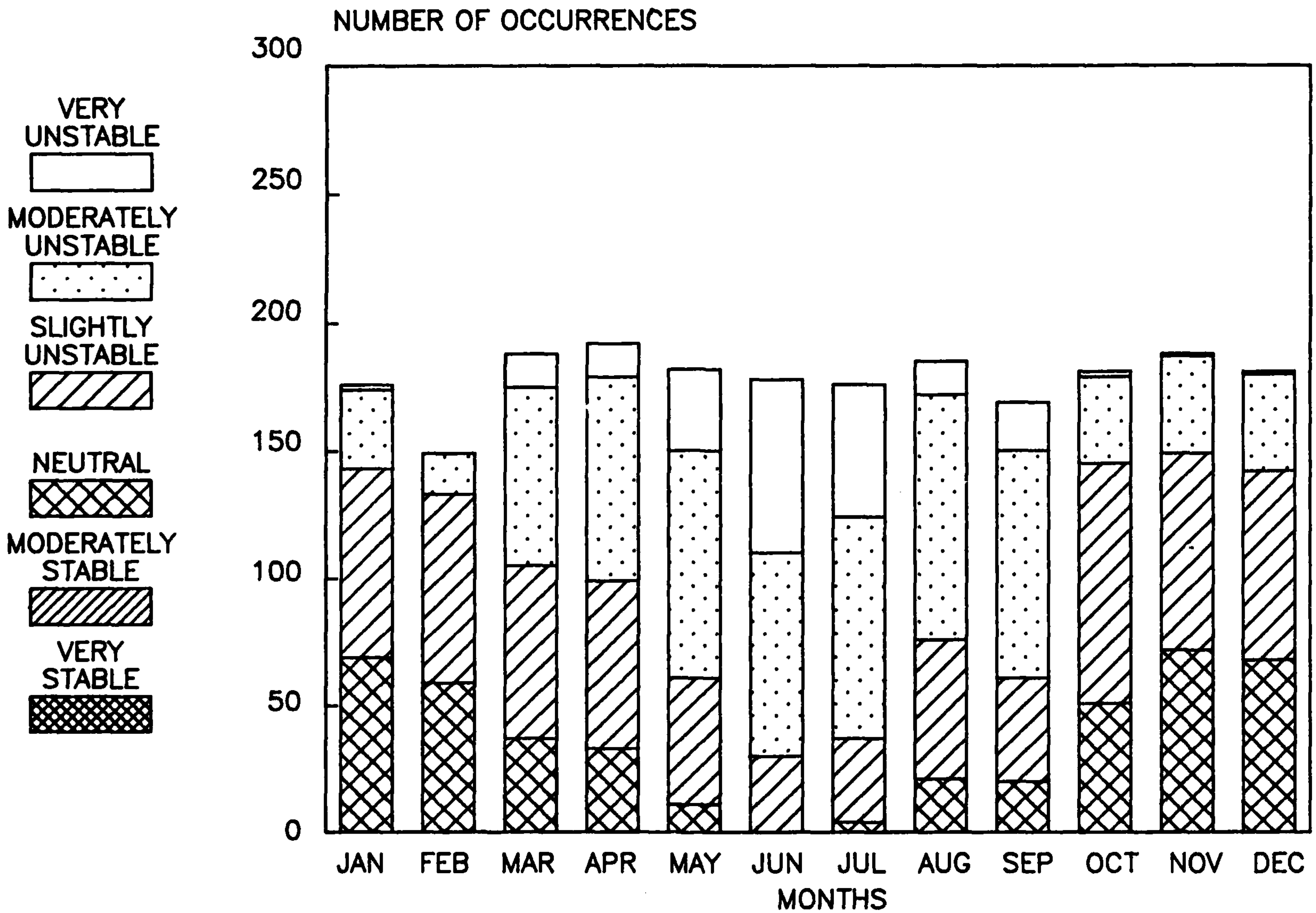
CONTROL DYNAMICS

HAHN 0600 GMT
STABILITY CRITERION



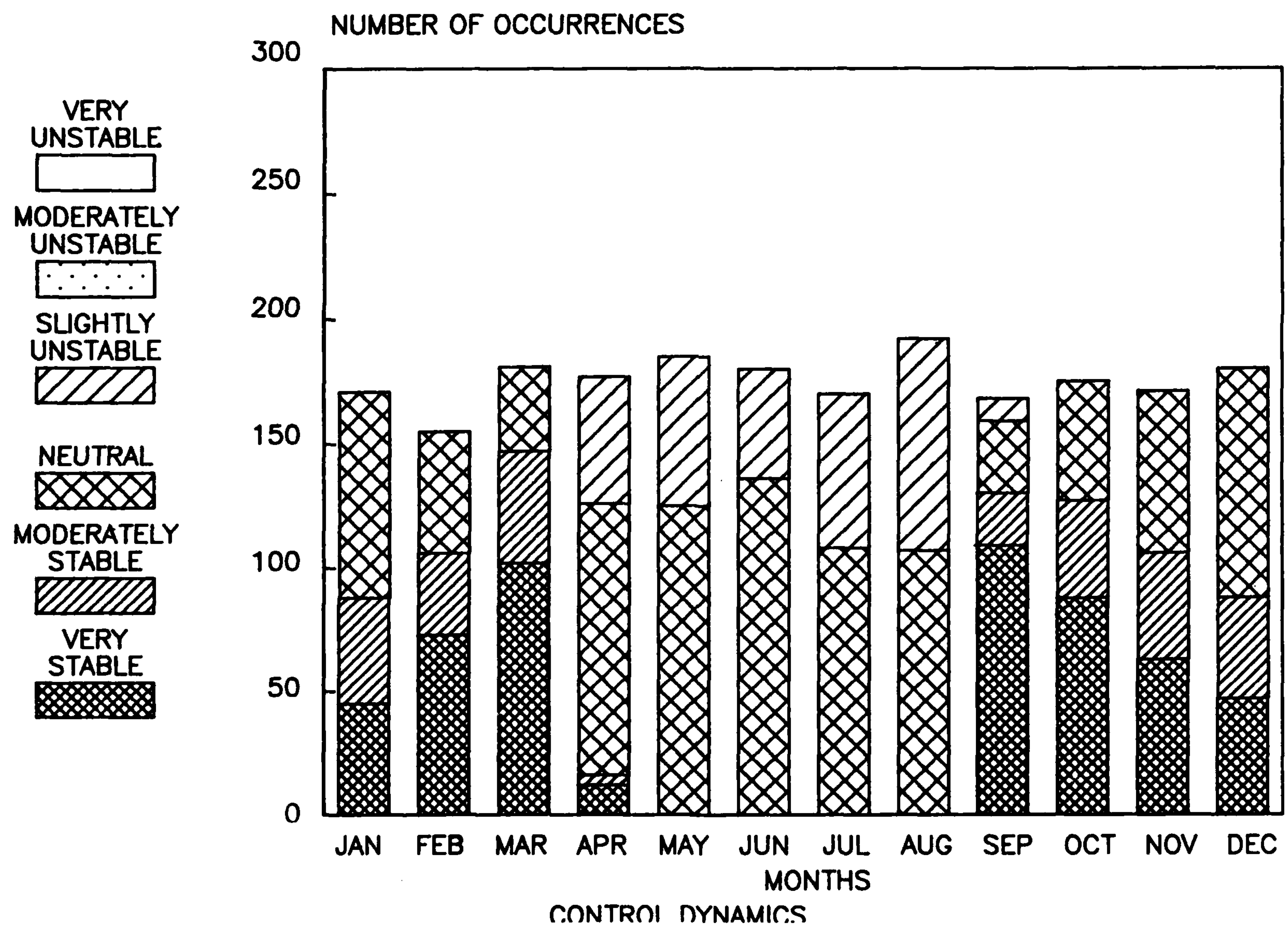
CONTROL DYNAMICS

HAHN 1200 GMT
STABILITY CRITERION

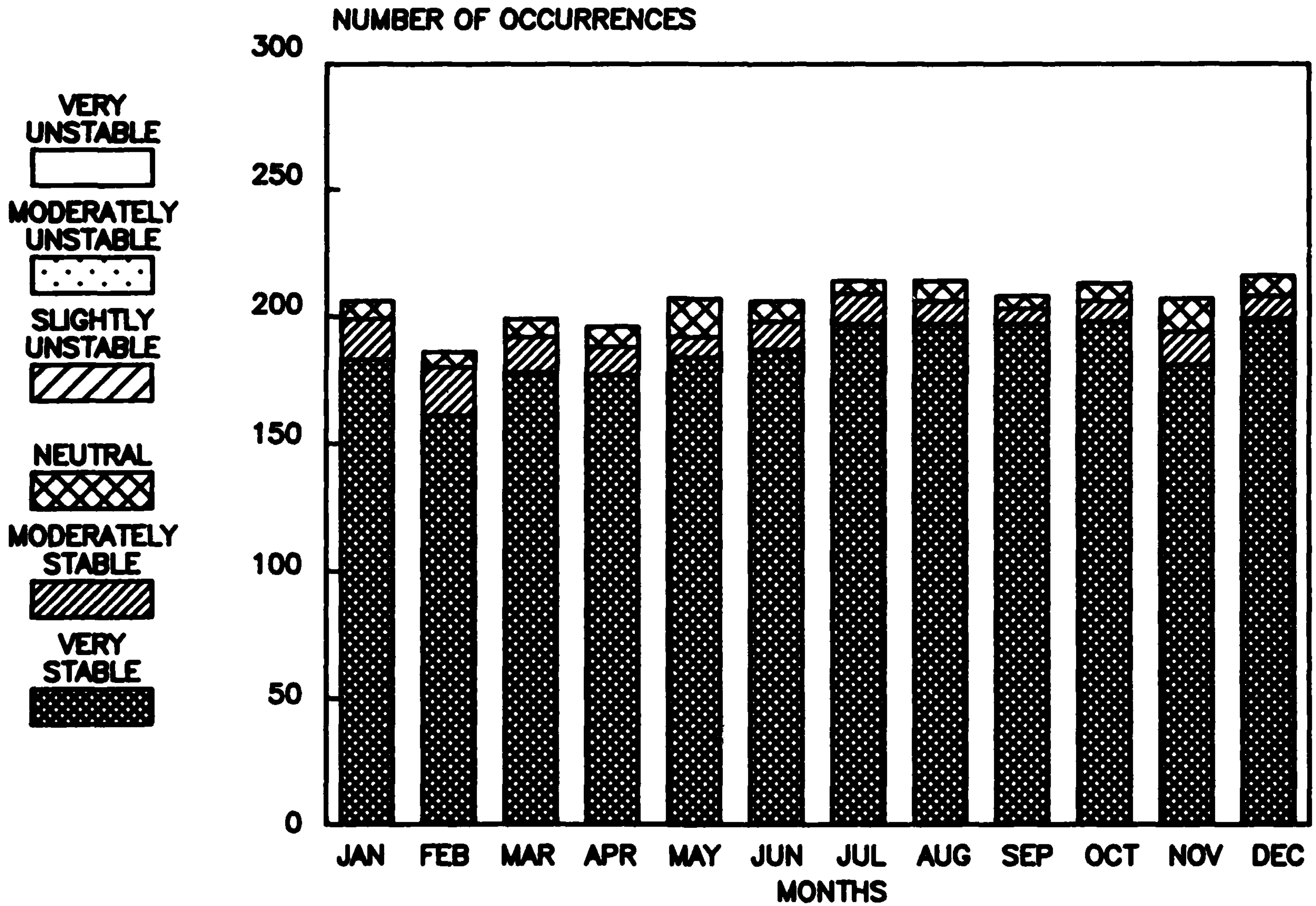


CONTROL DYNAMICS

HAHN 1800 GMT
STABILITY CRITERION

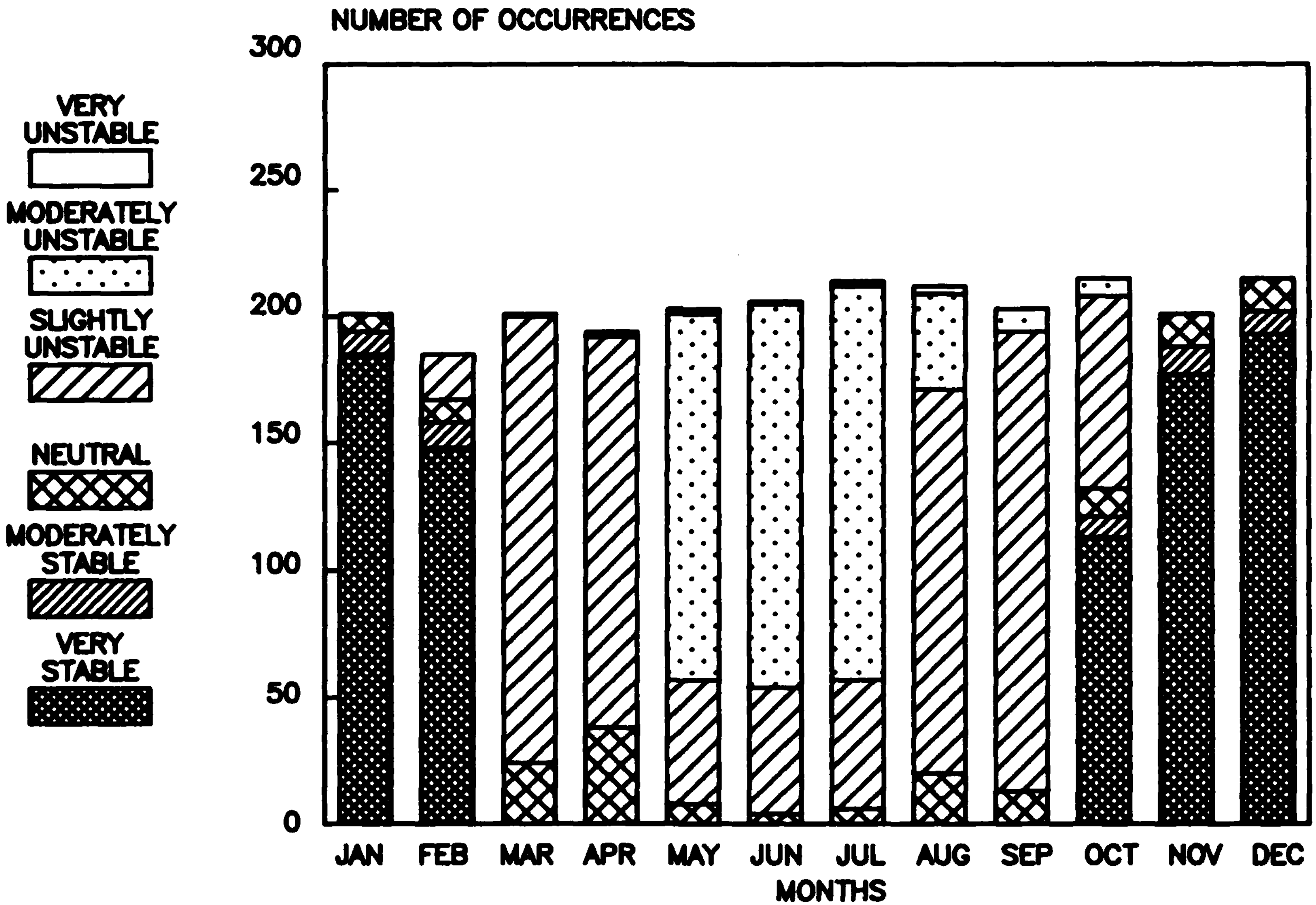


OSAN 0000 LOCAL STABILITY CRITERION

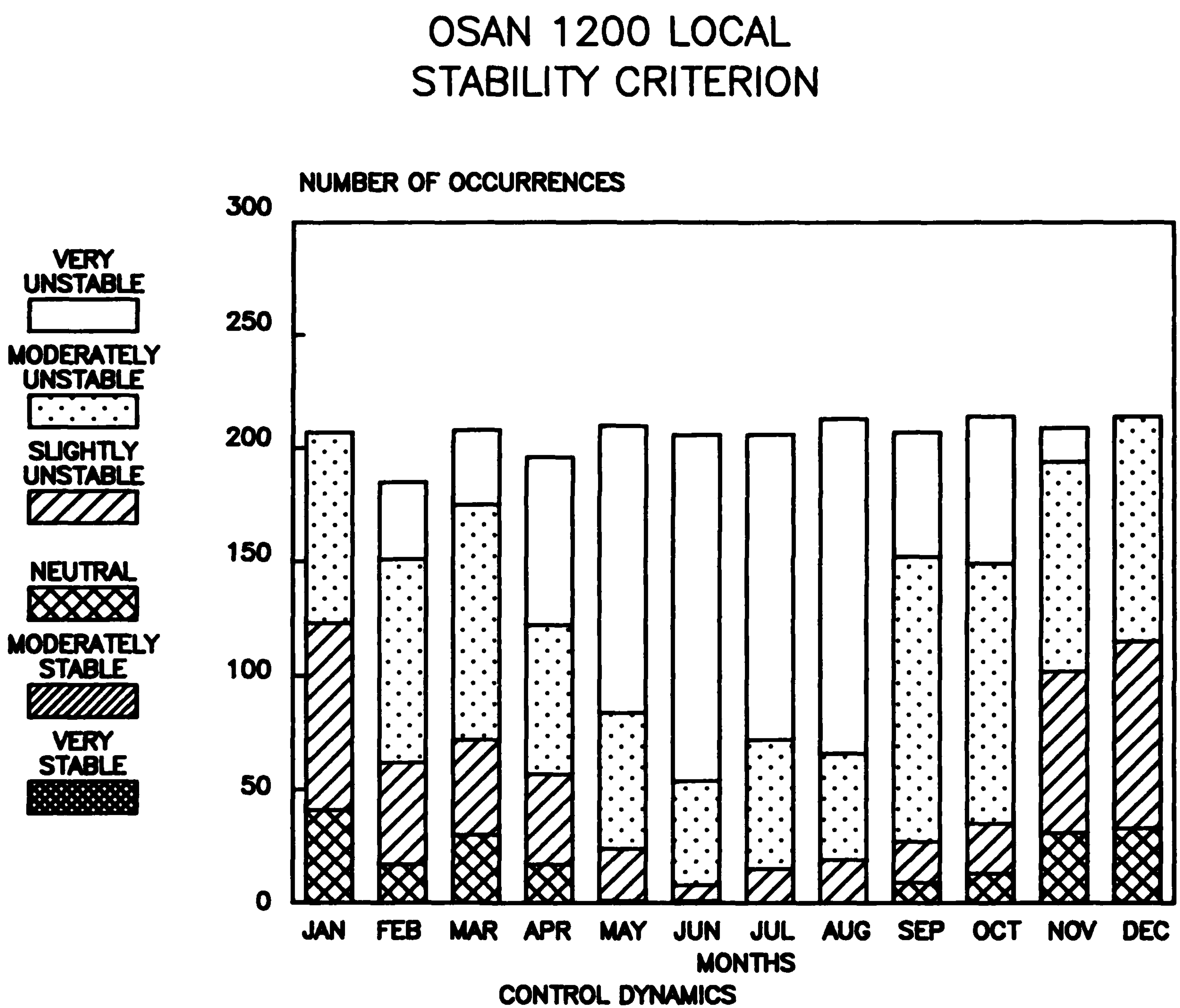


CONTROL DYNAMICS

OSAN 0600 LOCAL
STABILITY CRITERION

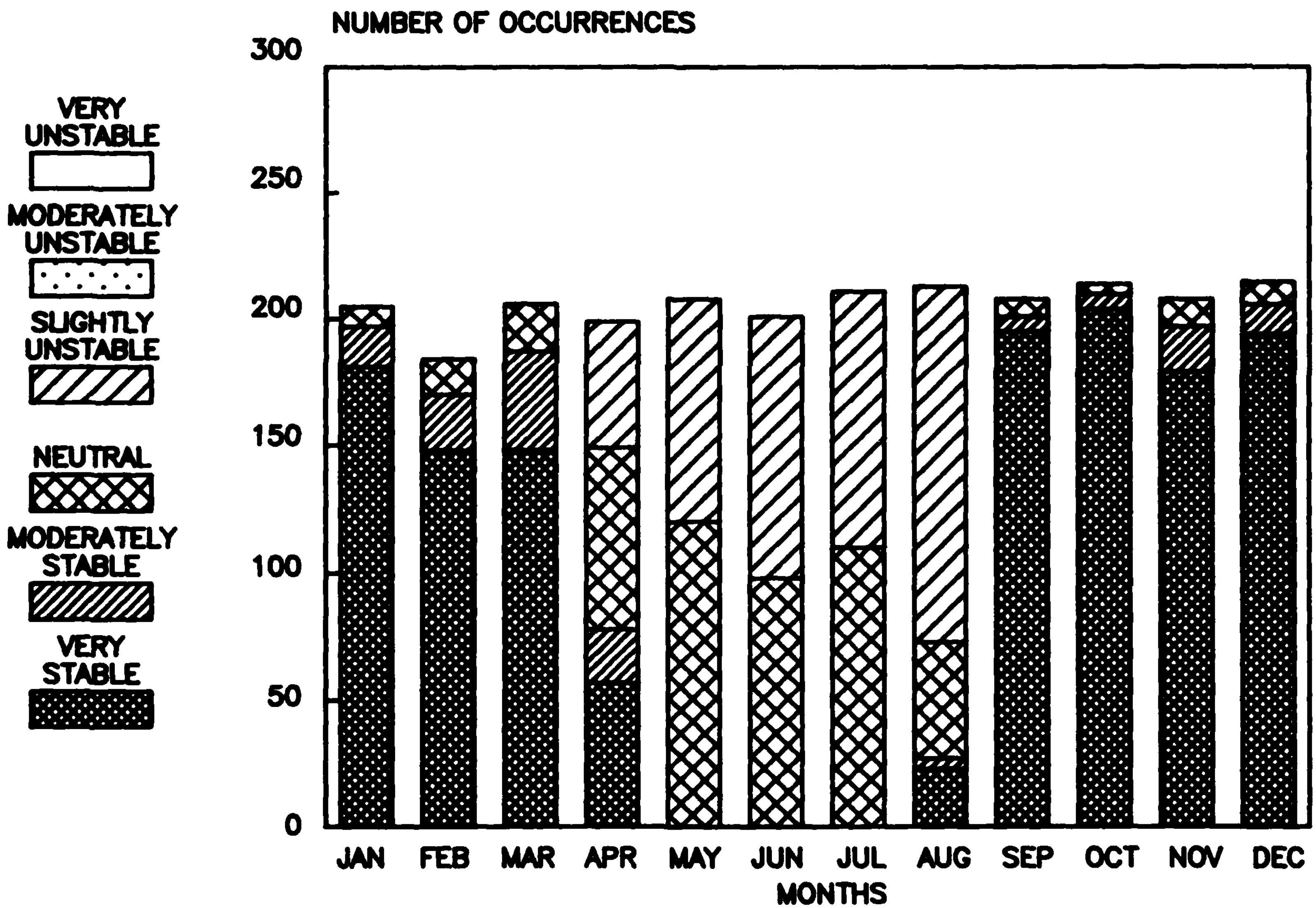


CONTROL DYNAMICS



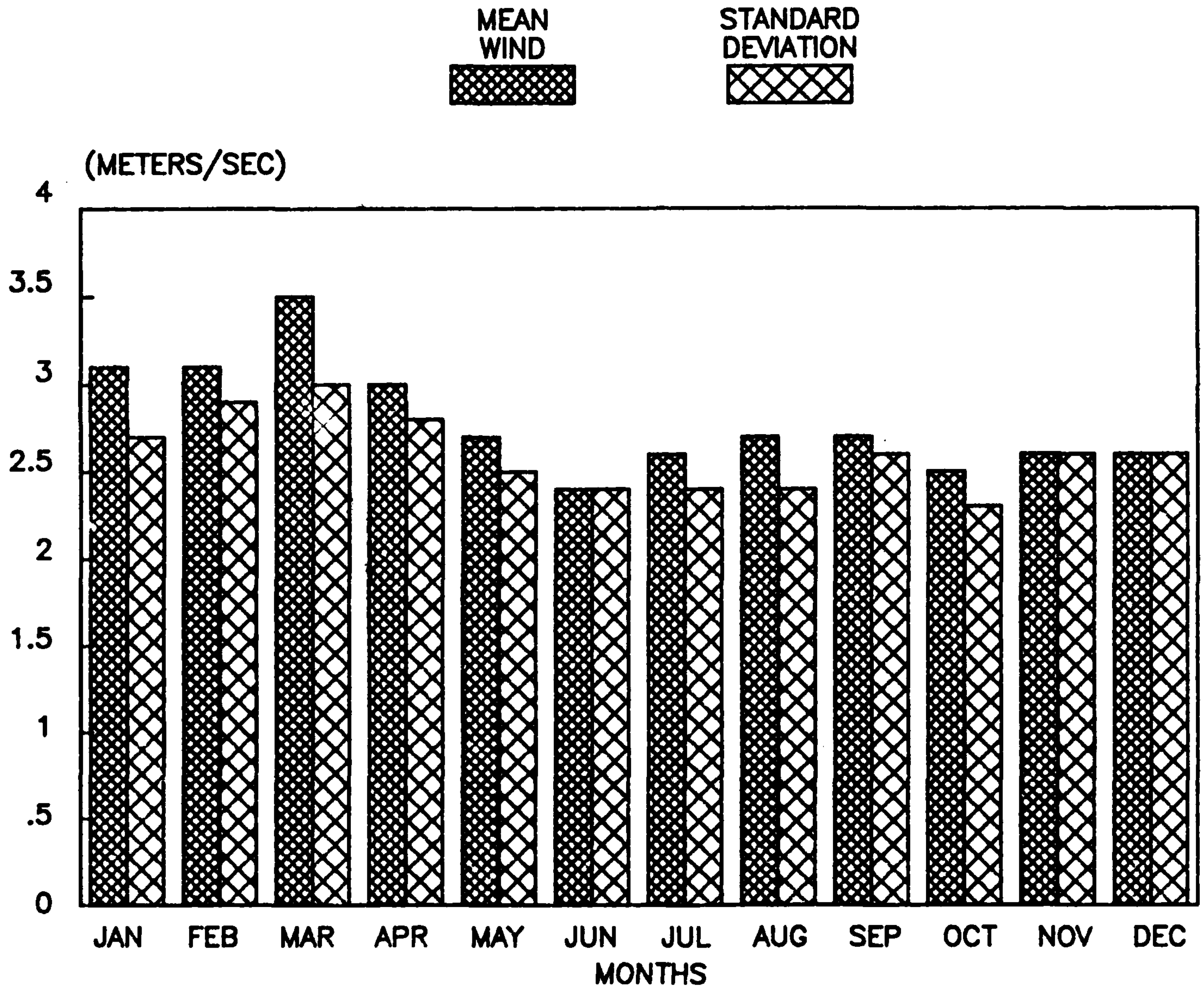
OSAN 1200 LOCAL
STABILITY CRITERION
NUMBER OF OCCURRENCES
300
250
200
150
100
50
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTHS
CONTROL DYNAMICS
VERY UNSTABLE
MODERATELY UNSTABLE
SLIGHTLY UNSTABLE
NEUTRAL
MODERATELY STABLE
VERY STABLE

OSAN 1800 LOCAL
STABILITY CRITERION

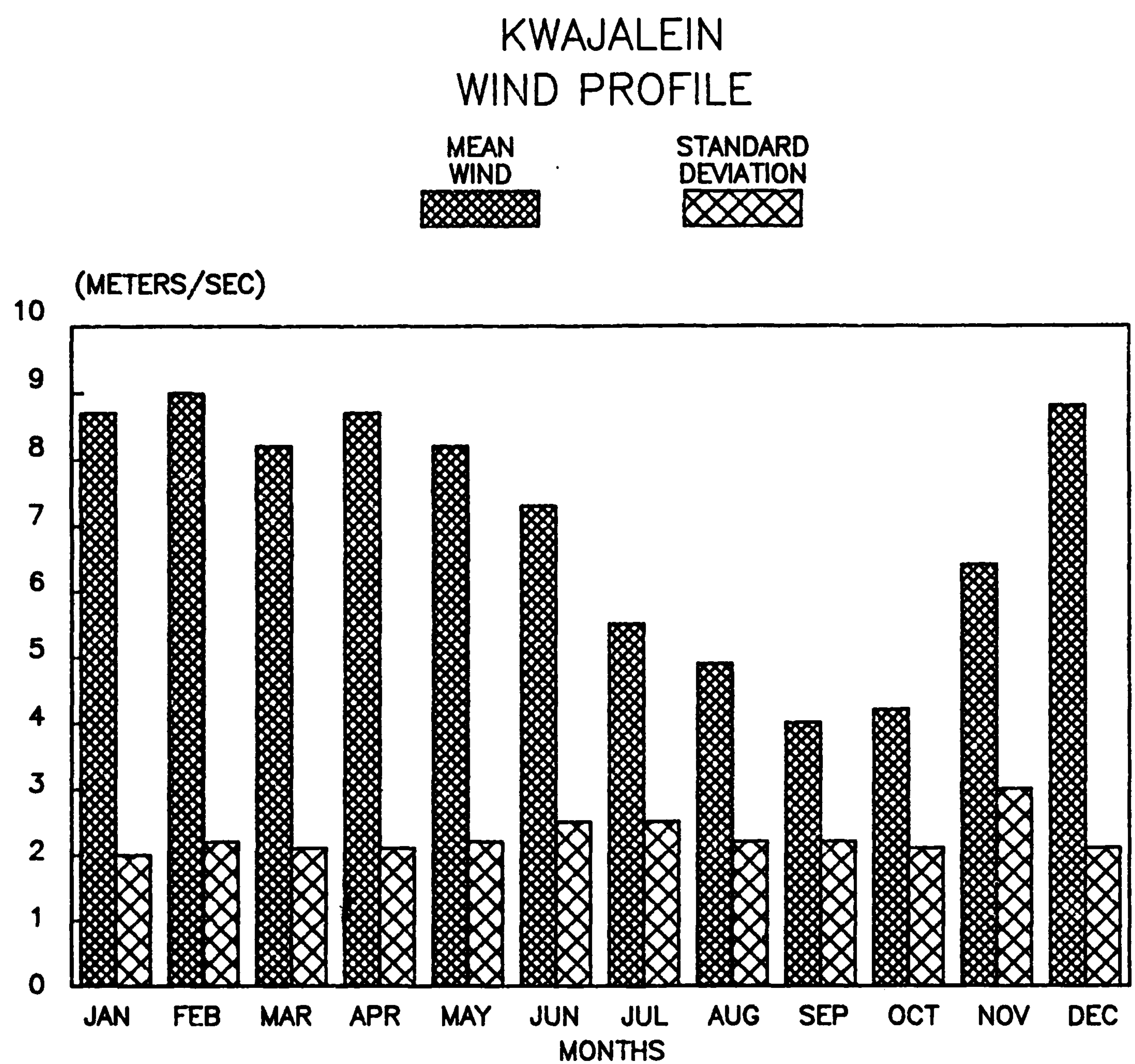


CONTROL DYNAMICS

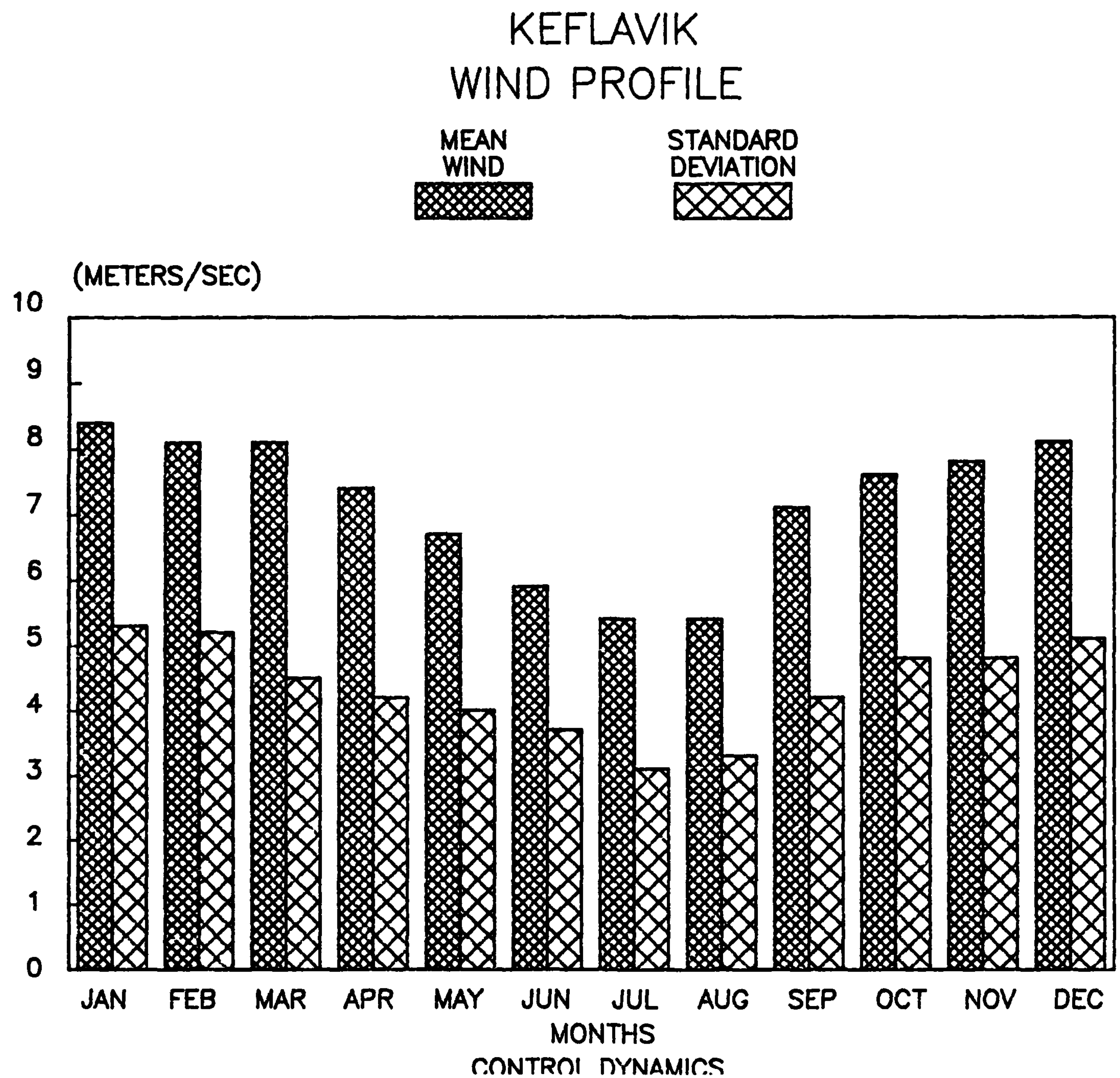
OSAN
WIND PROFILE



CONTROL DYNAMICS



CONTROL DYNAMICS


KEFLAVIK
WIND PROFILE
MEAN WIND
STANDARD DEVIATION
(METERS/SEC)
10
9
8
7
6
5
4
3
2
1
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
MONTHS
CONTROL DYNAMICS

9. SPATIAL MODELING

The topic of spatial modeling of wind is one in which significantly less work has been performed. The primary topics of concern for spatial turbulence models are the coherence of turbulence along with Taylor's hypothesis.

Over somewhat short distances (< 100-200 m) turbulence can be shown to be coherent to some degree in each axis. This coherence is typically represented as an exponentially decaying function such that the turbulence becomes more rapidly less coherent as the separation distance increases. Typical coherence curves as taken from Armendariz(3.1) are shown in the following figures.

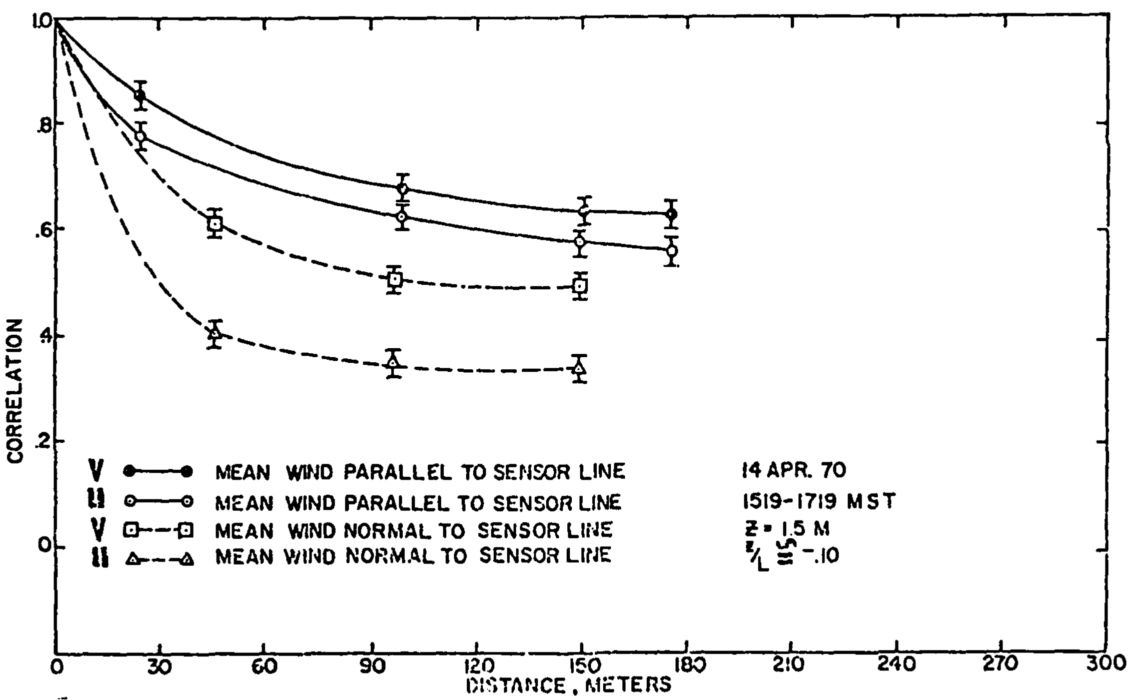


Figure 11. Zero-Lag horizontal wind component correlation at a height of 1.5 meter under unstable conditions as function of distance separation for mean wind parallel and normal to sensor line.

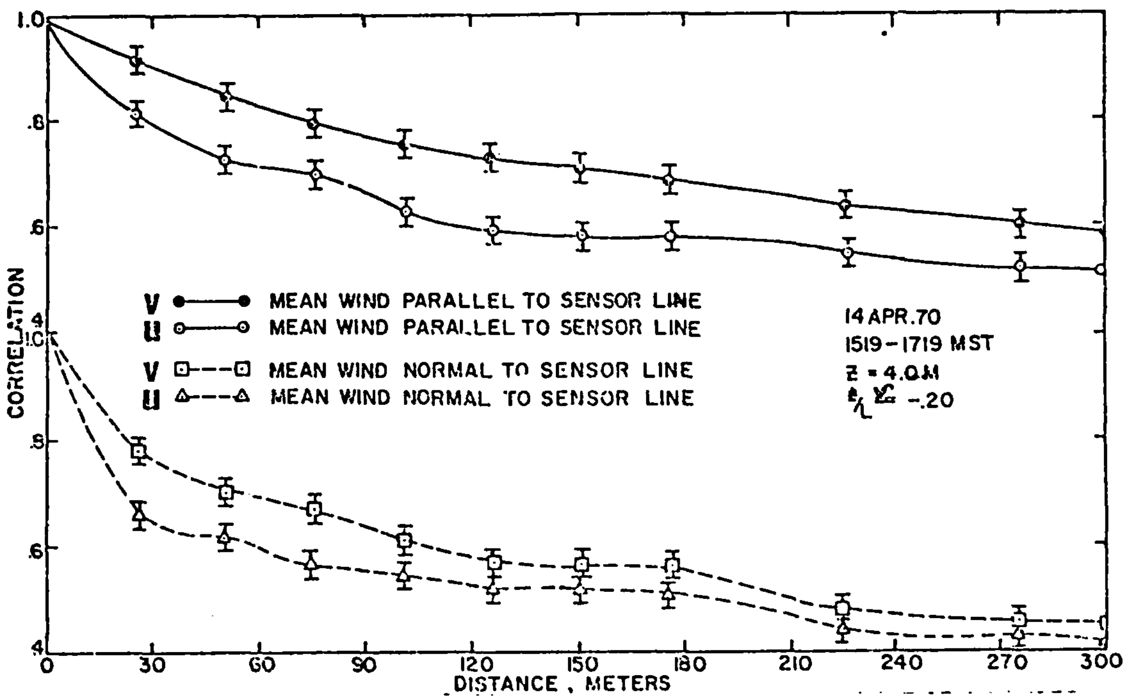


Figure 12. Zero-Lag horizontal wind component correlation at a height of 4 meter under unstable conditions as function of distance separation for mean wind parallel and normal to sensor line.

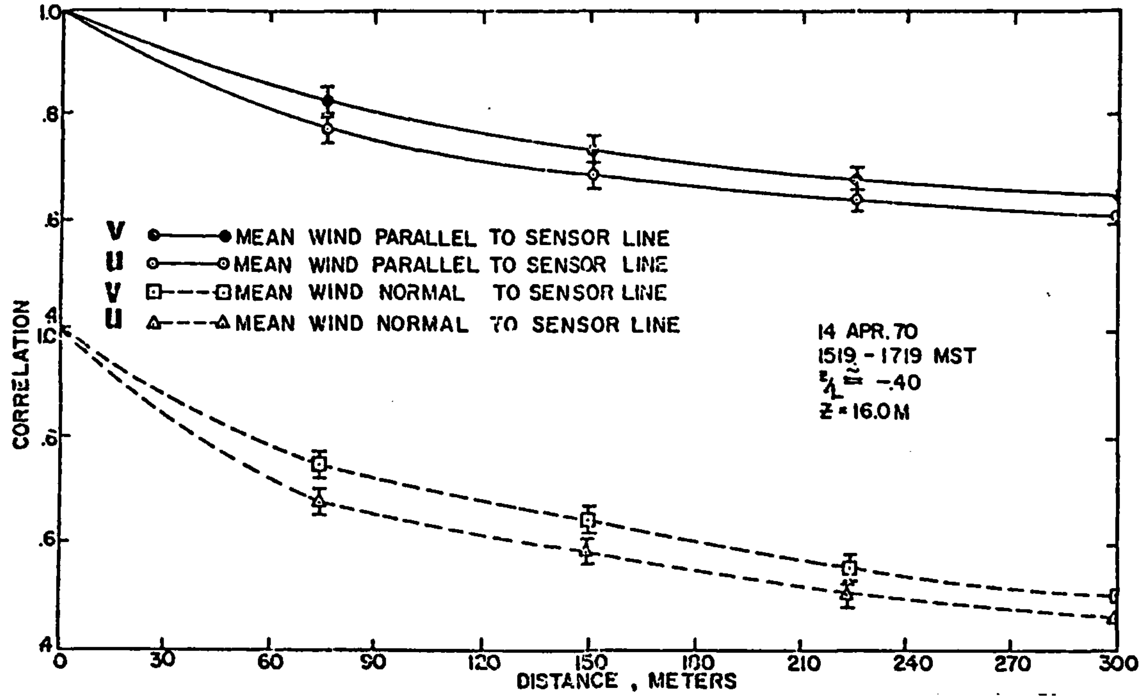


Figure 13. Zero-Lag horizontal wind component correlation at a height of 16 meter under unstable conditions as function of distance separation for mean wind parallel and normal to sensor line.

The rate at which the coherence decays is a function of separation distance, frequency, mean wind speed, and some decay constant as shown below.

$$\text{coh} = e^{-(awx/v)}$$

where a = decay constant
w = turbulence frequency
x = separation distance
v = reference velocity

Each of these terms is relatively straightforward except for the decay constant "a". While all authors include this term, few if any agree on its value. It seems to be somewhat arbitrarily chosen based on experience and data available.

This expression for coherence allows the following generalizations:

1. Strong winds show greater coherence than light winds.

2. Low frequency eddies show greater coherence than high frequencies.

3. Coherence decreases increasingly fast with separation distance.

4. Coherence is greater in an unstable atmosphere.

The modeling of coherence generally incorporates the use of many independent noise sources which are filtered and added before driving some turbulence filter function. The appropriate phase lagging of these input filters based on separation distance, reference velocity, and frequency produces correlated turbulent time series for a given separation distance. The form of the inter-level coherence model developed by Frost(6.31) is shown below.

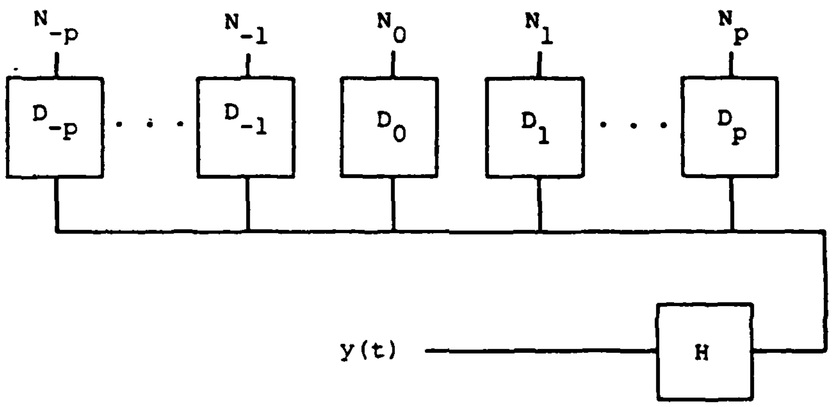


Figure 14. Inter-level coherence model

While this type of turbulence will have a significant impact on the study of structures or on the dynamics of large vehicles, it would seem that of greater importance to rocketry problems is a discussion of Taylor's hypothesis.

Taylor's hypothesis involves the assumption that turbulence is frozen in the mean wind, because the turbulence decays slowly with respect to the speed at which the observer passes through it. In other words, we might obtain about the same data by recording in time at a fixed location as we would by rapidly moving upstream against the mean wind.

To illustrate these ideas consider the record of an atmospheric variable A, observed at a fixed point as depicted in the following figure. On the assumption that turbulent eddies are carried by the mean wind "U" and change only slowly as they move, we could assume that the pattern in the figure is produced by having a spatial pattern in the "x" direction moving past the observer with speed "U" without change of shape. In other words, the spatial pattern could be depicted exactly as in the figure with the axis relabeled as "x=Ut". This notion is called the frozen wave hypothesis or Taylor's hypothesis(7.5).

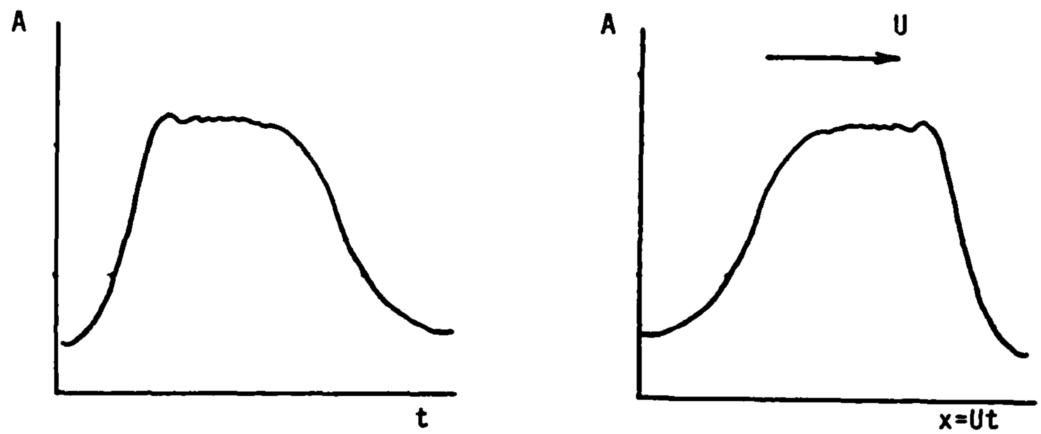


Figure 15. Illustration of Taylor's hypothesis

As is evident from the definition above, in order that Taylor's hypothesis be valid, it is necessary that the turbulence be stationary in time and homogeneous in the x direction. These conditions are often satisfied near the boundary layer when the terrain is consistent in roughness.

Work on the experimental validation of Taylor's hypothesis has been performed by Frost(5.9) at the Marshall Space Flight Center boundary layer tower array. In this experiment turbulence time series were taken at several towers aligned with the wind. This actual data was then compared to data which was taken at the upwind tower and scaled by the mean wind speed to produce a spatial turbulence series. According to Frost(5.9), this frozen and

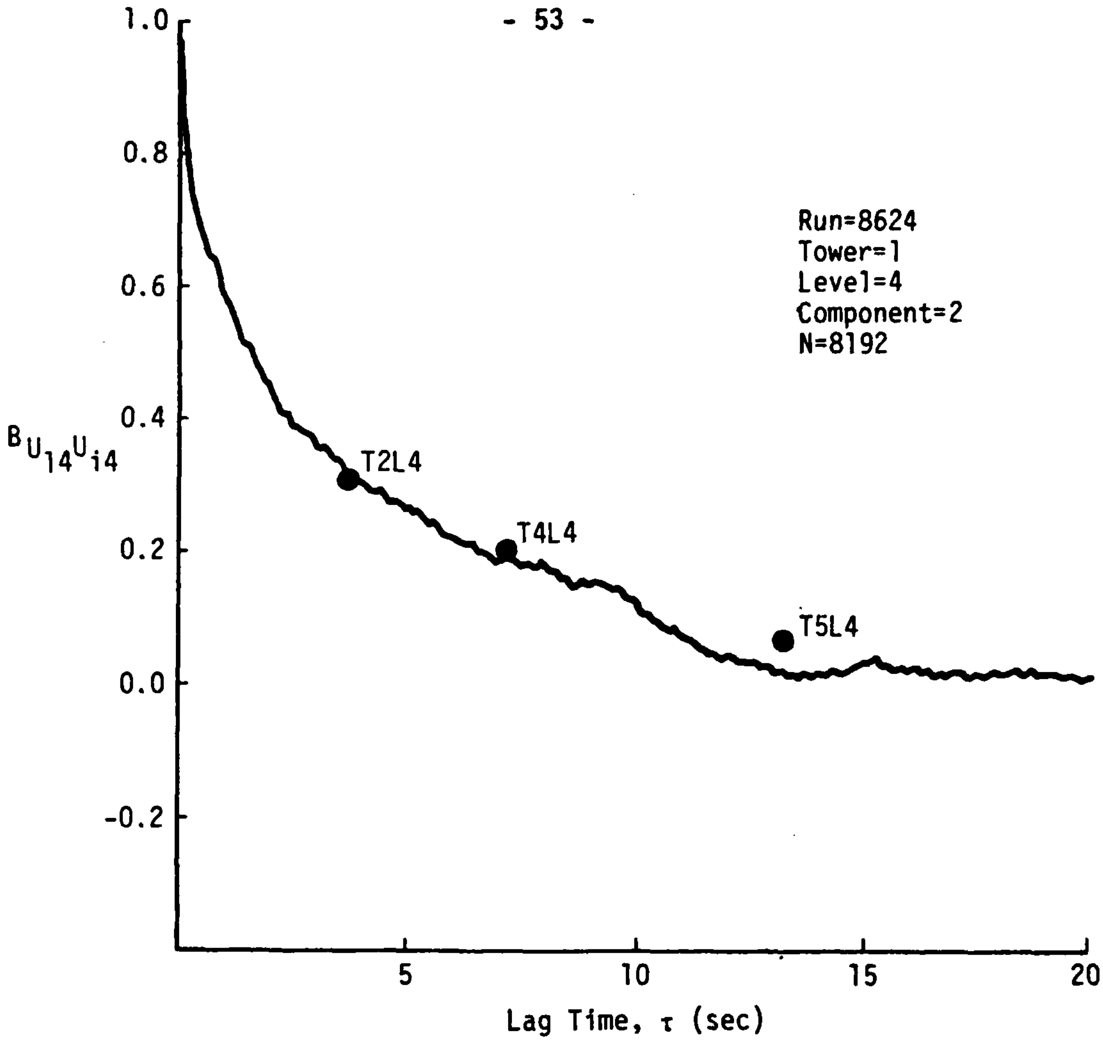


Figure 16. Illustration of validity of Taylor's hypothesis (● spatial correlation converted to time correlation with the relationship $\ell=\overline{w}\tau$).

scaled turbulence gave excellent agreement to what was actually measured at various points downwind. The following figure from Frost illustrates the agreement between actual data and data predicted by Taylor's hypothesis.

Thus it would seem that for terrain that is homogeneous in nature, Taylor's hypothesis provides a useful tool for obtaining a spatial wind history from a wind measurement.

A second point to be considered with Taylor's hypothesis involves the simulation of a turbulent time series. For the case in which a vehicle is moving through a turbulent field rapidly, the turbulence can be considered frozen. Then

scaling the time series by the vehicle airspeed produces a spatial series. Therefore for this type of situation a turbulence time series can be considered as spatial turbulence simply by scaling.

In summary, the consideration of correlation and Taylor's hypothesis are important for cases such as structure loading, where the separation distance between points of interest are relatively small. To expect a high correlation of turbulence 2 to 3 kilometers from a measurement site is however unrealistic. According to Armendariz(3.1), the coherence decreases to almost negligible values with horizontal separation greater than 200 meters even under unstable conditions, except for the long wavelength portion (>3000m). This suggests that one can only extrapolate the long wave portion of the wind energy beyond a few seconds and for greater distance than perhaps 200 meters. The short wave or turbulent portion appears to be quite intractable.

It becomes apparent that to predict significantly the wind conditions in the target area requires the use of remote measurements. Perhaps the most promising method of obtaining remote measurements without the use of downrange instruments is the utilization of LIDAR. Frost(5.8) has reported on the use of LIDAR in conjunction with an instrumented aircraft in the NASA gust gradient program. The LIDAR was used to take remote measurements of turbulence along the ILS approach path and was later compared to the data taken aboard the aircraft flying the approach. Good agreement was achieved between the LIDAR and the aircraft measurements.

10. FUTURE WORK

The next step would probably be the development of accurate mean wind and turbulence models, suitable for implementation into a 6DOF guided missile simulation. Due to the variety of simulations, the model would be incorporated into a designated system. The model would be capable of handling stable, neutral, or unstable atmospheric conditions, Gaussian or non-Gaussian distributed turbulence, general terrain roughness characterization, gust gradient effects, and coherent turbulence.

Models can be developed for tree line created turbulence or other major obstacles and verified with a three dimensional water tunnel flow simulation capability such as can be performed by FWG.

To access accurately the effects of variable wind, the standard equations of motion used to describe missile dynamics need to be expanded since they typically assume either no wind or a constant mean wind. The additional terms would include both temporal and spatial gradients of wind (Bowles and Frost 7.3). The relative importance of these terms and related changes to input parameters for the aerodynamic coefficients need to be assessed on a missile by missile basis.

The incorporation of accurate wind turbulence models allows for a more realistic assessment of dispersion of dumb rounds. One interesting possibility would be to try to optimize the design of the round to minimize the dispersion.

Since wind prediction based on correlation has been shown to be unrealistic beyond one or two hundred meters, the alternative of using LIDAR to measure data along the anticipated trajectory should be examined. Simulations would be used in the first phase to assess potential gains, followed by a subsequent phase that would involve actual use of LIDAR with the RAKE or some similar system that would allow for measurements to be taken at other than the launch site.

11. SUMMARY

Control Dynamics has performed as extensive survey of the literature available and pertinent to the problems associated with wind effects on free flight rockets. In addition to surveying the available literature, meetings and phone contacts have been held with individuals who are actively involved with research in the field of atmospheric science. The primary intent of these surveys and contacts has been to determine what type of work is being performed that has an impact on design and simulation of small missiles. It was also desired to establish areas which seem to be particularly important and which warrant further study.

Several areas which seem to be of interest include the use of the Space Shuttle Turbulence Tapes (SSTT), the approximation of the von Karman spectra with a linear expression, the effects of atmospheric stability on turbulence intensity, mean wind data, and several issues concerning spatial modeling.

The Space Shuttle Turbulence Tapes provide a quick and relatively simple means of incorporating high quality turbulence data into current simulations. Reservations concerning the lack of high frequency content, mass storage problems, and necessity of always using the same turbulence would seem to indicate that the SSTT are primarily valid for large and slower vehicles.

The von Karman approximation method provides a compact, efficient, means of generating turbulence. The code is efficient enough to generate turbulence on an as needed basis instead of storing large blocks of data in mass storage. This provides an added benefit of generating independent sets of turbulence by changing the seeds on the random number generator. As shown in the plots in the body of this report, the turbulence provides a very close fit to the von Karman at all but very high frequencies.

A discussion of atmospheric stability along with data showing the type of changes that occurs on a daily, seasonal, and geographical basis has been included. This data has been presented in a bar chart form instead of the original tabular form in order to provide increased clarity and ease of interpretation. The data shows that the changes in atmospheric stability are sufficient to warrant including in a realistic wind turbulent model. The effects of stability are typically ignored in most turbulence models, but several methods exist which would allow the accurate modeling of stability effects on turbulence intensity. These include scaling the spectra

by a gain, low pass filtering the turbulence, or the use of an alternate spectra such as the Kaimal which includes stability terms.

Data for mean winds and standard deviations at 35 sites in the northern hemisphere is available in tabular form. This data was presented in bar chart form for 3 sites in order to show a representative sample of the available data.

Various topics have been discussed regarding spatial modeling of wind. These include the inclusion of coherence and Taylor's hypothesis into a model and the usefulness of these techniques. The use of coherence modeling and Taylor's have been shown to be valid and important for situations concerned with the modeling of wind over relatively short distances(<200m). It becomes evident however, that at large distances such as occur in rocketry problems (2-3km) these techniques are no longer valid. The best that can be expected in wind prediction over long ranges is to characterize the general statistics of the wind.

The local measurements allow the rough prediction of mean wind and turbulence intensity along with the basic spectra that is being observed. This of course assumes homogeneous terrain. If the terrain has large irregularities between launch and target sites, then it may be impossible to predict accurately the effects of wind on the rocket downrange. The basic problems involving long range wind predictions are the following.

1. Turbulence degrades excessively as it moves downrange due to the long time it takes to be blown downwind.

2. Terrain is more likely to be inhomogeneous over long distances.

3. Wind is unlikely to be aligned along the path of the missile. In this case the measurement may be biased by terrain near the launch site. This terrain is likely to be different from the terrain along the flight path.

Additional improvements in wind measurements could be made by using advanced instrumentation such as LIDAR to give directly measured downrange wind measurements. Additional sophistication in modeling could be obtained through the use of advanced numerical models in combination with water tunnel simulation of complex terrain.

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13. APPENDIX

This appendix contains listings to the computer programs used to produce the turbulence time series by approximation of the von Karman spectra. These programs were written and supplied by Dr. Warren Campbell at Marshall Space Flight Center and were modified by Control Dynamics to run on a HP9040.

```
      PROGRAM DRATL
C--------------------------------------------------------------------
C
C ***************  LONGITUDINAL ****************
C
C THIS PROGRAM GENERATES "TURBULENCE" USING A 2-3 RATIONAL
C APPROXIMATION TO THE VON KARMAN SPECTRUM.
C
C PROGRAMMER: DR. WARREN CAMPBELL (NASA MARSHALL SPACE FLIGHT CENTER)
C
C REVISOR: DAVID EDGEMON (CONTROL DYNAMICS CO.)
C--------------------------------------------------------------------
c     DIMENSION IPAR(5)
      REAL*8 Y0,Y1,Y2,YN,X0,X1,X2,X3,ELS0,ELS1,ELS2,ELS3,R0,R1,R2,R3
     & ,DT,PI,EX1,EX2,EX3,EX12,EX13,EX23,EX123
      REAL*8 P1,P2,P3,Z1,Z2,A,B,C,D,XK1,SUM,SUMSQ,YBAR,Y2BAR
      INTEGER*4 ITER,NPTS
        integer irow,ix,iy
        real*8 sig,xb,xdp,xp
        real*8 avk,alpha,el,s1,sigma,v,time,yp
c
        integer nrec,icol,j
        real outv(2)
c
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      COMMON/EXPBL/ EX1,EX2,EX3,EX12,EX13,EX23,EX123
c
        open(unit=1,form='unformatted',file='plot1.dat',access='direct'
     &,recl=4)
        open(unit=2,file='plot2.dat')
        open(unit=3,file='time.dat')
c
        icol=2
        irow=0
c
        write(6,*) 'enter standard deviation for random numbers'
        read(5,*) sig
        write(6,*) 'enter mean of random numbers'
        read(5,*) xb
        write(6,*) 'enter seed for random numbers'
        read(5,*) ix
c
c     CALL RMPAR(IPAR)
C----------------------------------------
c     LUPRT = IPAR(1)
C----------------------------------------
C
C SET UP CONSTANTS
C
      AVK = 1.339
      WRITE(6,5999)
5999  FORMAT(' ENTER NUMBER OF POINTS')
      READ(5,*) NPTS
      WRITE(6,7998)
7998  FORMAT(' ENTER DT IN DOUBLE PRECISION')
      READ(5,*) DT
```

```
      PI = 4.*DATAN(1.D0)
      ITER = 0
      SUM = 0.D0
      SUMSQ = 0.0D0
      WRITE(6,7999)
7999  FORMAT(' ENTER DESIRED SIGMA')
      READ(5,*) SIGMA
      S1 = SIGMA
D     WRITE(6,8999) PI
8999  FORMAT(' PI=',D15.10)
C
C INITIALIZE THE X'S AND Y'S
C
      CALL INITal(Y0,Y1,Y2,X0,X1,X2,X3,TIME,ITER,sig,xb,xdp,xp,ix,iy)
D     WRITE(6,8998) TIME
8998  FORMAT(' TIME=',F10.5)
C
C GET SIGMA, V,  AND TURBULENT LENGTH SCALE
C
100   CONTINUE
      CALL SVL(DT,SIGMA,V,EL)
      ALPHA = V*DT/EL
      SIGMA = S1/(.8762*ALPHA**0.49626)
D     WRITE(6,8997)
8997  FORMAT(' SVL')
C
C CALCULATE POLES AND ZEROES
C
      CALL PANDZ(P1,P2,P3,Z1,Z2)
D     WRITE(6,8996) P1,P2,P3,Z1,Z2
8996  FORMAT(' POLES=',3(2X,D15.9)/' ZEROES=',3(2X,D15.9))
C
C CALCULATE COEFFICIENTS
C
      CALL COEFF(P1,P2,P3,Z1,Z2,A,B,C,D,XK1)
D     WRITE(6,8995) A,B,C,D,XK1
8995  FORMAT(' COEFF A,B,C,D,XK1=',5(2X,E15.9))
C
C CALCULATE RHS DIFFERENCE EQUATION COEFFICIENTS
C
      CALL RI(P1,P2,P3,A,B,C,D,R0,R1,R2,R3)
D     WRITE(6,8994) R0,R1,R2,R3
8994  FORMAT(' RI=',4(2X,D15.9))
C
C CALCULATE DIFFERENCE EQN LEFT SIDE COEFFICIENTS
C
      CALL LI(P1,P2,P3,A,B,C,D,ELS0,ELS1,ELS2,ELS3)
D     WRITE(6,8993) ELS0,ELS1,ELS2,ELS3
8993  FORMAT(' LI=',4(2X,D15.9))
C
C ITERATE
C
      YN = ELS1*Y2 - ELS2*Y1 + ELS3*Y0 + R0*X3 - R1*X2 + R2*X1
     &  - R3*X0
      ITER = ITER + 1
      SUM = SUM + YN
```

```
          SUMSQ = SUMSQ + YN*YN
          YBAR = SUM/ITER
          Y2BAR = DSQRT(SUMSQ/ITER -YBAR**2)
D         WRITE(6,8900) Y2,Y1,Y0,X3,X2,X1,X0
8900      FORMAT(' Y2,Y1,Y0=',3(2X,D15.9)/' X3,X2,X1,X0=',4(2X,D15.9))
          Y0 = Y1
          Y1 = Y2
          Y2 = YN
          X0 = X1
          X1 = X2
          X2 = X3
            call random (sig,xb,xdp,xp,ix,iy)
          X3 = xdp
D         WRITE(6,9998) X3
9998      FORMAT(' RANDOM NUMBER=',F10.6)
          TIME = TIME + DT
          YP = YN
          WRITE(6,9999) TIME,YP
c
c           write data to plot files
c
            outv(1)=time
            outv(2)=yp
            do 1234 j=1,icol
            nrec=nrec+1
            write(1,rec=nrec) outv(j)
1234        continue
c
c           write data to file for psd program
c
            write(3,'(e13.7)') yp
            irow=irow+1
c
c
9999      FORMAT(' TIME=',E12.6,'  Y=',E15.9)
          IF(ITER .LT. NPTS) GO TO 100
          WRITE(6,9980) NPTS,YBAR,Y2BAR
9980      FORMAT(' NPTS=',I8,'  YBAR=',D15.9,'  Y2BAR=',D15.9)
c
            write(2,'(2i5)') icol,irow
            write(2,'(a8)') 'time'
            write(2,'(a8)') 'turb'
c
c          IF(LUPRT .EQ. 8) ENDFILE 8
c
            close(unit=1)
            close(unit=2)
c
          STOP
          END
c
c
          SUBROUTINE INITal(Y0,Y1,Y2,X0,X1,X2,X3,TIME,ITER
         &,sig,xb,xdp,xp,ix,iy)
          REAL*8 Y0,Y1,Y2,X0,X1,X2,X3,time
          INTEGER*4 ITER
```

```
        real*8 sig,xb,xdp,xp
        integer ix,iy
      X0 = 0.D0
      X1 = 0.D0
      X2 = 0.D0
        call random (sig,xb,xdp,xp,ix,iy)
      X3 = xdp
      Y0 = 0.D0
      Y1 = 0.D0
      Y2 = 0.D0
      TIME = 0.
      ITER = 0
      RETURN
      END
c
c
      SUBROUTINE SVL(DT,SIGMA,V,EL)
        real*8 dt,sigma,el,s1,v
      S1 = SIGMA
      V = 100.
      EL = 500.
      RETURN
      END
c
c
      SUBROUTINE PANDZ(P1,P2,P3,Z1,Z2)
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      REAL*8 P1,P2,P3,Z1,Z2,C,PI,DT
        real*8 avk,el,p1p,p2p,p3p,sigma,v,z1p,z2p
      INTEGER*4 ITER
      DATA Z1P/-1.46821076/,Z2P/-5.388932143/,P1P/-1.02025059/
     *,P2P/-1.67661571/,P3P/-8.10313370/
      C = V/(AVK*EL)
      P1 = P1P*C
      P2 = P2P*C
      P3 = P3P*C
      Z1 = Z1P*C
      Z2 = Z2P*C
      RETURN
      END
c
c
      SUBROUTINE COEFF(P1,P2,P3,Z1,Z2,A,B,C,D,XK1)
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      REAL*8 P1,P2,P3,Z1,Z2,A,B,C,D,XK1,DT,PI
        real*8 avk,el,sigma,v
      INTEGER*4 ITER
      XK1 = SIGMA*DSQRT(EL/(V*PI))
      XK1 = XK1*(-P1*P2*P3)/(Z1*Z2)
      A = XK1*(P1-Z1)*(P1-Z2)/(P1*(P1-P2)*(P1-P3))
      B = XK1*(P2-Z1)*(P2-Z2)/(P2*(P2-P1)*(P2-P3))
      C = XK1*(P3-Z1)*(P3-Z2)/(P3*(P3-P1)*(P3-P2))
      D = -XK1*Z1*Z2/(P1*P2*P3)
      RETURN
      END
c
```

```
c
      SUBROUTINE RI(P1,P2,P3,A,B,C,D,R0,R1,R2,R3)
      REAL*8 DT,PI,P1,P2,P3,A,B,C,D,R0,R1,R2,R3,EX1,EX2,EX3,EX12,EX13
     & ,EX23,EX123
      INTEGER*4 ITER
        real*8 avk,el,sigma,v
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      COMMON/EXPBL/ EX1,EX2,EX3,EX12,EX13,EX23,EX123
      EX1 = DEXP(P1*DT)
D     WRITE(6,9999) EX1
9999  FORMAT(' EX1=',D15.9)
      EX2 = DEXP(P2*DT)
D     WRITE(6,9998) EX2
9998  FORMAT(' EX2=',D15.9)
      EX3 = DEXP(P3*DT)
D     WRITE(6,9997) EX3
9997  FORMAT(' EX3=',D15.9)
      EX12= DEXP((P1+P2)*DT)
D     WRITE(6,9996) EX12
9996  FORMAT(' EX12=',D15.9)
      EX13= DEXP((P1+P3)*DT)
D     WRITE(6,9995) EX13
9995  FORMAT(' EX13=',D15.9)
      EX23= DEXP((P2+P3)*DT)
D     WRITE(6,9994) EX23
9994  FORMAT(' EX23=',D15.9)
      EX123= DEXP((P1+P2+P3)*DT)
D     WRITE(6,9993) EX123
9993  FORMAT(' EX123=',D15.9)
      R0 = A + B + C + D
D     WRITE(6,9989) R0
9989  FORMAT(' R0=',D15.9)
      R1 = A*(1.+EX2+EX3)+B*(1.+EX1+EX3)+C*(1.+EX1+EX2)+
     &  D*(EX1+EX2+EX3)
      R2 = A*(EX2+EX3+EX23)+B*(EX1+EX3+EX13)+C*(EX1+EX2+EX12)+
     &  D*(EX12+EX13+EX23)
      R3 = A*EX23+B*EX13+C*EX12+D*EX123
D     WRITE(6,9992) R0,R1,R2,R3
9992  FORMAT(' R0=',D15.9,'  R1=',D15.9,'  R2=',D15.9,'  R3=',D15.9)
      RETURN
      END
c
c
      SUBROUTINE LI(P1,P2,P3,A,B,C,D,ELS0,ELS1,ELS2,ELS3)
      REAL*8 EX1,EX2,EX3,EX12,EX13,EX23,EX123,PI,DT
      REAL*8 P1,P2,P3,A,B,C,D,ELS0,ELS1,ELS2,ELS3
        real*8 avk,el,sigma,v
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      COMMON/EXPBL/ EX1,EX2,EX3,EX12,EX13,EX23,EX123
      INTEGER*4 ITER
      ELS0 = 1.D0
      ELS1 = EX1 + EX2 + EX3
      ELS2 = EX12 + EX13 + EX23
      ELS3 = EX123
      RETURN
      END
```

```
c
c
      BLOCK DATA EX
      REAL*8 DT,PI,EX1,EX2,EX3,EX12,EX13,EX23,EX123
      INTEGER*4 ITER
        real*8 avk,el,sigma,v
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      COMMON/EXPBL/ EX1,EX2,EX3,EX12,EX13,EX23,EX123
      END
c
c
c
        subroutine random (sig,xb,xdp,xp,ix,iy)
        real*8 xp,a,xdp,sig,xb
        integer iy,ix,j
c
        a=0.0
        do 30 j=1,12
c
        iy=ix*65539
        if(iy) 10,20,20
10      iy=iy+2147483647+1
20      xp=iy
        xp=xp/2147483647.d0
        ix=iy
30      a=a+xp
        xdp=(a-6.0)*sig+xb
c
        return
        end
```

```
      PROGRAM DTRNS
C-------------------------------------------------------------
C
C ***************  TRANSVERSE  ***************
C
C THIS PROGRAM GENERATES "TURBULENCE" USING A 3-4 RATIONAL
C APPROXIMATION TO THE VON KARMAN TRANSVERSE SPECTRUM.
C
C PROGRAMMER: DR. WARREN CAMPBELL (NASA MARSHALL SPACE FLIGHT CENTER)
C
C REVISOR: DAVID EDGEMON (CONTROL DYNAMICS CO.)
C-------------------------------------------------------------
c      DIMENSION IPAR(5)
      REAL*8 Y0,Y1,Y2,Y3,YN,X0,X1,X2,X3,X4,ELS0,ELS1,ELS2,ELS3,ELS4
     & ,R0,R1,R2,R3,R4
     & ,DT,PI,EX1,EX2,EX3,EX4,EX12,EX13,EX14,EX23,EX24,EX34,EX123,EX124
     & ,EX134,EX234,X1234
      REAL*8 P1,P2,P3,P4,Z1,Z2,Z3,A,B,C,D,F,XK1,SUM,SUMSQ,YBAR,Y2BAR
        real*8 avk,alpha,el,s1,sigma,v,time,yp
      INTEGER*4 ITER,NPTS
c
        real*8 sig,xb,xdp,xp
        integer ix,iy,irow,icol
c
        integer nrec,j
        real outv(2)
c
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      COMMON/EXPBL/ EX1,EX2,EX3,EX4,EX12,EX13,EX14,EX23,EX24
     &,EX34,EX123,EX124,EX134,EX234,X1234
c      CALL RMPAR(IPAR)
C-------------------------------------
c      LUPRT = IPAR(1)
C-------------------------------------
c
        open(unit=1,form='unformatted',file='plot1.dat',access='direct'
     &,recl=4)
        open(unit=2,file='plot2.dat')
        open(unit=3,file='time.dat')
c
        irow=0
        icol=2
c
        write(6,*) 'enter standard deviation for random numbers'
        read(5,*) sig
        write(6,*) 'enter mean of random numbers'
        read(5,*) xb
        write(6,*) 'enter seed for random numbers'
        read(5,*) ix
c
      WRITE(6,5999)
5999  FORMAT(' ENTER NPOINTS')
      READ(5,*) NPTS
C
C SET UP CONSTANTS
C
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```
      AVK = 1.339
      WRITE(6,7998)
7998  FORMAT(' ENTER DT IN DOUBLE PRECISION')
      READ(5,*) DT
      PI = 4.*DATAN(1.D0)
      ITER = 0
      SUM = 0.D0
      SUMSQ = 0.0D0
      WRITE(6,7999)
7999  FORMAT(' ENTER SIGMA')
      READ(5,*) SIGMA
      S1 = SIGMA
D     WRITE(6,8999) PI
8999  FORMAT(' PI=',D15.10)
C
C INITIALIZE THE X'S AND Y'S
C
      CALL INITal(Y0,Y1,Y2,Y3,X0,X1,X2,X3,X4,TIME,ITER)
D     WRITE(6,8998) TIME
8998  FORMAT(' TIME=',F10.5)
C
C GET SIGMA, V,  AND TURBULENT LENGTH SCALE
C
100   CONTINUE
      CALL SVL(SIGMA,V,EL)
      ALPHA = V*DT/EL
      SIGMA = S1/(1.233*ALPHA**0.4976)
D     WRITE(6,8997)
8997  FORMAT(' SVL')
C
C CALCULATE POLES AND ZEROES
C
      CALL PANDZ(P1,P2,P3,P4,Z1,Z2,Z3)
D     WRITE(6,8996) P1,P2,P3,P4,Z1,Z2,Z3
8996  FORMAT(' POLES=',4(2X,D15.9)/' ZEROES=',3(2X,D15.9))
C
C CALCULATE COEFFICIENTS
C
      CALL COEFF(P1,P2,P3,P4,Z1,Z2,Z3,A,B,C,D,F,XK1)
D     WRITE(6,8995) A,B,C,D,F,XK1
8995  FORMAT(' COEFF A,B,C,D,F,XK1=',6(2X,E15.9))
C
C CALCULATE RHS DIFFERENCE EQUATION COEFFICIENTS
C
      CALL RI(P1,P2,P3,P4,A,B,C,D,F,R0,R1,R2,R3,R4)
D     WRITE(6,8994) R0,R1,R2,R3,R4
8994  FORMAT(' RI=',5(2X,D15.9))
C
C CALCULATE DIFFERENCE EQN LEFT SIDE COEFFICIENTS
C
      CALL LI(P1,P2,P3,P4,A,B,C,D,F,ELS0,ELS1,ELS2,ELS3,ELS4)
D     WRITE(6,8993) ELS0,ELS1,ELS2,ELS3,ELS4
8993  FORMAT(' LI=',5(2X,D15.9))
C
C ITERATE
C
```

```
          YN = ELS1*Y3 - ELS2*Y2 + ELS3*Y1 - ELS4*Y0 + R0*X4 - R1*X3 + R2*X2
         &  - R3*X1 + R4*X0
          ITER = ITER + 1
          SUM = SUM + YN
          SUMSQ = SUMSQ + YN*YN
          YBAR = SUM/ITER
          Y2BAR = DSQRT(SUMSQ/ITER -YBAR**2)
    D     WRITE(6,8900) Y3,Y2,Y1,Y0,X4,X3,X2,X1,X0
    8900  FORMAT(' Y3,Y2,Y1,Y0=',4(2X,D15.9)/',X4,X3,X2,X1,X0=',5(2X,D15.9))
          Y0 = Y1
          Y1 = Y2
          Y2 = Y3
          Y3 = YN
          X0 = X1
          X1 = X2
          X2 = X3
          X3 = X4
            call random (sig,xb,xdp,xp,ix,iy)
          X4 = xdp
    D     WRITE(6,9998) X4
    9998  FORMAT(' RANDOM NUMBER=',F10.6)
          TIME = TIME + DT
          YP = YN
          WRITE(6,9999) TIME,YP
    c
    c       write data to plot files
    c
            outv(1)=time
            outv(2)=yp
            do 1234 j=1,icol
            nrec=nrec+1
            write(1,rec=nrec) outv(j)
    1234    continue
            write(3,'(e13.7)') yp
            irow=irow+1
    c
    c
    9999  FORMAT(' TIME=',E12.6,'  Y=',E15.9)
          IF(ITER .LT. NPTS) GO TO 100
          WRITE(6,9980) NPTS,YBAR,Y2BAR
    9980  FORMAT(' NPTS=',I8,'  YBAR=',D15.9,'  Y2BAR=',D15.9)
    c     IF(LUPRT .EQ. 8) ENDFILE 8
    c
            write(2,'(2i5)') icol,irow
            write(2,'(a8)') 'time'
            write(2,'(a8)') 'turb'
    c
          STOP
          END
    c
    c
          SUBROUTINE INITal(Y0,Y1,Y2,Y3,X0,X1,X2,X3,X4,TIME,ITER)
          REAL*8 Y0,Y1,Y2,Y3,X0,X1,X2,X3,X4,time
          INTEGER*4 ITER
          X0 = 0.D0
          X1 = 0.D0
```

```
      X2 = 0.D0
      X3 = 0.0D0
      Y0 = 0.D0
      Y1 = 0.D0
      Y2 = 0.D0
      Y3 = 0.0D0
      TIME = 0.
      ITER = 0
      RETURN
      END
c
c
      SUBROUTINE SVL(SIGMA,V,EL)
        real*8 sigma,el,v
      V = 100.
      EL = 500.
      RETURN
      END
c
c
      SUBROUTINE PANDZ(P1,P2,P3,P4,Z1,Z2,Z3)
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      REAL*8 P1,P2,P3,P4,Z1,Z2,Z3,C,PI,DT,P1P,P2P,P3P,P4P,Z1P,Z2P,Z3P
        real*8 avk,el,sigma,v
      INTEGER*4 ITER
      DATA Z1P/-1.46821076D0/,Z2P/-5.388932143D0/,Z3P/-0.612372436D0/
     &  ,P1P/-1.02025059D0/
     *,P2P/-1.67661571D0/,P3P/-8.10313370D0/,P4P/-1.D0/
      C = V/(AVK*EL)
      P1 = P1P*C
      P2 = P2P*C
      P3 = P3P*C
      P4 = P4P*C
      Z1 = Z1P*C
      Z2 = Z2P*C
      Z3 = Z3P*C
      RETURN
      END
c
c
      SUBROUTINE COEFF(P1,P2,P3,P4,Z1,Z2,Z3,A,B,C,D,F,XK1)
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      REAL*8 P1,P2,P3,P4,Z1,Z2,Z3,A,B,C,D,F,XK1,DT,PI
        real*8 avk,el,sigma,v
      INTEGER*4 ITER
      XK1 = SIGMA*DSQRT(EL/(V*PI))
      XK1 = XK1*(-P1*P2*P3*P4)/(Z1*Z2*Z3)
      A = XK1*(P1-Z1)*(P1-Z2)*(P1-Z3)/(P1*(P1-P2)*(P1-P3)*(P1-P4))
      B = XK1*(P2-Z1)*(P2-Z2)*(P2-Z3)/(P2*(P2-P1)*(P2-P3)*(P2-P4))
      C = XK1*(P3-Z1)*(P3-Z2)*(P3-Z3)/(P3*(P3-P1)*(P3-P2)*(P3-P4))
      D = XK1*(P4-Z1)*(P4-Z2)*(P4-Z3)/(P4*(P4-P1)*(P4-P2)*(P4-P3))
      F = -XK1*Z1*Z2*Z3/(P1*P2*P3*P4)
      RETURN
      END
c
c
```

```
      SUBROUTINE RI(P1,P2,P3,P4,A,B,C,D,F,R0,R1,R2,R3,R4)
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      COMMON/EXPBL/ EX1,EX2,EX3,EX4,EX12,EX13,EX14,EX23,EX24
     &,EX34,EX123,EX124,EX134,EX234,X1234
        real*8 avk,el,sigma,v
      REAL*8 DT,PI,P1,P2,P3,P4,A,B,C,D,F,R0,R1,R2,R3,R4,EX1,EX2,EX3,
     &  EX4,EX12,EX13,EX14,EX23,EX24,EX34,EX123,EX124,EX134,EX234,X1234
      INTEGER*4 ITER
      EX1 = DEXP(P1*DT)
D     WRITE(6,9999) EX1
9999  FORMAT(' EX1=',D15.9)
      EX2 = DEXP(P2*DT)
D     WRITE(6,9998) EX2
9998  FORMAT(' EX2=',D15.9)
      EX3 = DEXP(P3*DT)
D     WRITE(6,9997) EX3
9997  FORMAT(' EX3=',D15.9)
      EX4 = DEXP(P4*DT)
D     WRITE(6,9980) EX4
9980  FORMAT(' EX4=',D15.9)
      EX12= DEXP((P1+P2)*DT)
D     WRITE(6,9996) EX12
9996  FORMAT(' EX12=',D15.9)
      EX13= DEXP((P1+P3)*DT)
D     WRITE(6,9995) EX13
9995  FORMAT(' EX13=',D15.9)
      EX14 = DEXP((P1+P4)*DT)
D     WRITE(6,9989) EX14
9989  FORMAT(' EX14=',D15.9)
      EX23= DEXP((P2+P3)*DT)
D     WRITE(6,9994) EX23
9994  FORMAT(' EX23=',D15.9)
      EX24 = DEXP((P2+P4)*DT)
D     WRITE(6,9970) EX24
9970  FORMAT(' EX24=',D15.9)
      EX34 = DEXP((P3+P4)*DT)
D     WRITE(6,9969) EX34
9969  FORMAT(' EX34=',D15.9)
      EX123= DEXP((P1+P2+P3)*DT)
D     WRITE(6,9993) EX123
9993  FORMAT(' EX123=',D15.9)
      EX124 = DEXP((P1+P2+P4)*DT)
D     WRITE(6,9968) EX124
9968  FORMAT(' EX124=',D15.9)
      EX134 = DEXP((P1+P3+P4)*DT)
D     WRITE(6,9967) EX134
9967  FORMAT(' EX134=',D15.9)
      EX234 = DEXP((P2+P3+P4)*DT)
D     WRITE(6,9966) EX234
9966  FORMAT(' EX234=',D15.9)
      X1234 = DEXP((P1+P2+P3+P4)*DT)
D     WRITE(6,9965) X1234
9965  FORMAT(' X1234=',D15.9)
c
      R0 = A + B + C + D + F
D     WRITE(6,9960) R0
```

```
9960  FORMAT(' R0=',D15.9)
c
      R1 = A*(1. + EX2 + EX3 + EX4) + B*(1. + EX1 + EX3 + EX4)
     & + C*(1. + EX1 + EX2 + EX4) + D*(1. + EX1 + EX2 + EX3)
     & + F*(EX1 + EX2 + EX3 + EX4)
D     WRITE(6,9959) R1
9959  FORMAT(' R1=',D15.9)
c
      R2 = A*(EX2 + EX3 + EX4 + EX23 + EX24 + EX34)
     &    + B*(EX1 + EX3 + EX4 + EX13 + EX14 + EX34)
     &    + C*(EX1 + EX2 + EX4 + EX12 + EX14 + EX24)
     &    + D*(EX1 + EX2 + EX3 + EX12 + EX13 + EX23)
     &    + F*(EX12 + EX13 + EX14 + EX23 + EX24 + EX34)
D     WRITE(6,9958) R2
9958  FORMAT(' R2=',D15.9)
c
      R3 = A*(EX23 + EX24 + EX34 + EX234)
     &    + B*(EX13 + EX14 + EX34 + EX134)
     &    + C*(EX12 + EX14 + EX24 + EX124)
     &    + D*(EX12 + EX13 + EX23 + EX123)
     &    + F*(EX123 + EX124 + EX134 + EX234)
D     WRITE(6,9957) R3
9957  FORMAT(' R3=',D15.9)
c
      R4 = A*EX234 + B*EX134 + C*EX124 + D*EX123 + F*X1234
c
D     WRITE(6,9992) R0,R1,R2,R3,R4
9992  FORMAT(' R0=',D15.9,'  R1=',D15.9,'  R2=',D15.9,'  R3='
     &,D15.9,'  R4=',D15.9)
      RETURN
      END
c
c
      SUBROUTINE LI(P1,P2,P3,P4,A,B,C,D,F,ELS0,ELS1,ELS2,ELS3,ELS4)
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      COMMON/EXPBL/ EX1,EX2,EX3,EX4,EX12,EX13,EX14,EX23,EX24
     &,EX34,EX123,EX124,EX134,EX234,X1234
        real*8 avk,el,sigma,v
      REAL*8 EX1,EX2,EX3,EX4,EX12,EX13,EX14,EX23,EX24,EX34,EX123
     & ,EX124,EX134,EX234,X1234,PI,DT
      REAL*8 P1,P2,P3,P4,A,B,C,D,F,ELS0,ELS1,ELS2,ELS3,ELS4
      INTEGER*4 ITER
      ELS0 = 1.D0
      ELS1 = EX1 + EX2 + EX3 + EX4
      ELS2 = EX12 + EX13 + EX14 + EX23 + EX24 + EX34
      ELS3 = EX123 + EX124 + EX134 + EX234
      ELS4 = X1234
      RETURN
      END
c
c
      BLOCK DATA EX
      COMMON/CFF/ SIGMA,V,ITER,AVK,EL,DT,PI
      COMMON/EXPBL/ EX1,EX2,EX3,EX4,EX12,EX13,EX14,EX23,EX24
     &,EX34,EX123,EX124,EX134,EX234,X1234
        real*8 avk,el,sigma,v
```

```
      REAL*8 DT,PI,EX1,EX2,EX3,EX4,EX12,EX13,EX14,EX23,EX24,EX34,EX123
     & ,EX124,EX134,EX234,X1234
      INTEGER*4 ITER
      END
c
c
        subroutine random (sig,xb,xdp,xp,ix,iy)
        real*8 xp,a,xdp,sig,xb
        integer iy,ix,j
c
        a=0.0
        do 30 j=1,12
c
        iy=ix*65539
        if(iy) 10,20,20
10      iy=iy+2147483647+1
20      xp=iy
        xp=xp/2147483647.d0
        ix=iy
30      a=a+xp
        xdp=(a-6.0)*sig+xb
c
        return
        end
```

14. LIST OF ATTACHMENTS

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